THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

Review of Australian Diesel Particulate Matter Standard for Underground Coal Mines

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ABSTRACT

The link between diesel exhaust and cancer proposed by the National Institute for Occupational Safety and Health in 1998 has led to intensive research by various health organisations. Essentially, underground mine workers are the most exposed group to diesel particulates. As such, the mining industry has taken significant initiatives to reduce the level of exposure. This is to ensure that there is a safer and healthier working environment for their workers, resulting in increased productivity.

Australia has undertaken much of the research in the health effects associated with diesel particulates and the control technologies available to reduce the level of diesel particulate matter (DPM). However, research lacks definitive data evidence to suggest the effectiveness of the current exposure standard of 0.1 mg/m^3 elemental carbon (EC). Essentially, it is believed that the current standard is balanced by minimising the effects of irritation and potential risk of lung cancer, and the standard limit is achievable as a best practice. However, with current instruments that are capable of measuring real-time total carbon (TC) and EC data, it is appropriate that the exposure standard to be reassessed.

This study aims to investigate and review the current Australian DPM exposure standard for underground coal mines, through analysis of TC and EC data from Mine A underground longwall coal mine in Central Queensland. The personal sampling method was used to collect the data, where sampling equipment was attached to workers, recording the quantity of DPM during their shift. Sampling was conducted by the site supervisor, and as such, the collection method was assumed to be done accordingly and accurately, resulting in minimal errors. The aim is achieved through investigating the compliance of the data based on TC/EC ratio analysis and evaluating the correlation between TC and EC.

Analysis of the compliance of TC and EC data found that a total of 24 out of the 91 samples collected in the years 2014, 2015 and 2016 were out of compliance with the current DPM standard. As such it can be concluded that there is sufficient evidence to support the idea of reviewing the current DPM standard. Further analysis of relationship between TC and EC has shown a very strong linear relationship. This suggests that using EC only as a surrogate for DPM is insufficient, but both TC and EC should be considered, as practiced in the United States.

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ABBREVIATIONS

DPM	Diesel Particulate Matter
EC	Elemental Carbon
TC	Total Carbon
OC	Organic Carbon
UQ	University of Queensland
NIOSH	National Institute for Occupational Safety and Health
USA	United States of America
USEPA	United States Environmental Protection Agency
CO	Carbon Monoxide
HC	Hydrocarbon
NO	Nitrogen Oxide
RCD	Respirable Combustible Dust
MSHA	Mine Safety and Health Administration
OEL	Occupational Exposure Limit
NSW	New South Wales
TERA	Toxicology Excellence for Risk Assessment
PDM	Personal Dust Monitoring
LHD	Load, Haul and Dump

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1 INTRODUCTION

1.1 BACKGROUND

The mining industry encompasses a wide range of employees from multiple disciplines who are subject to many more hazards compared to other industries. Particularly, in underground mining, operation is in a confined area and under a significant volume of overburden. Many of the hazards have resulted in severe fatalities, therefore, significant improvement on safety controls were imposed through regulations and safety mining practices. However, there are other hazards that are either not well understood, or their level of risk is not commonly recognised. Diesel particulate matter is categorised as such a hazard.

The invention of the first stroke diesel engine in the 1980s by Rudolph Diesel was seen as the origin of diesel particulate matter. The adverse health effects associated with diesel particulate matter were not recognised until late 1988, when the National Institute for Occupational Safety and Health (NIOSH) proposed the existing link between diesel exhaust and cancer (NIOSH, 1998). Since then, there has been significant research on the development of measurement and controlling technologies of both the gas and particulate components of diesel exhausts.

DPM is defined as a sub-micron physical aerosol component of diesel exhaust, which is less than 1.0 micron and forms as the result of incomplete combustion of diesel fuels in diesel powered engines. The diesel exhaust contains gaseous phase and particulate fraction. The carbon component from diesel emission is made up of organic carbon (OC) and EC, commonly known as total TC, and accounts for 85% of the DPM (Belle, 2008).

Underground mine workers are high-risk exposure group to diesel particulate as they work near diesel vehicles. As such, there has been significant research undertaken in various areas concerning DPM. This includes the health effects of diesel particulates and control technologies available to reduce exposure.

The current accepted industry standard practiced in Australia is 0.1 mg/m^3 EC, where EC is used as surrogate. However, ‘to what extent diesel particulate matter is considered a risk?’ and ‘are the current exposure limits still effective?’ are questions that suggest further investigation was required. Therefore, a review of the Australian DPM standard exposure limits in underground coal mine is the area this research study will base its content on. This is to ensure that the current exposure limit is still effective, as the safety of underground coal miners in Australia is very important.

To investigate the effectiveness of the current standard, EC and TC were collected from Mine A underground coal mine in Central Queensland. Mine A utilised a longwall mining operation, where diesel equipment is used in their operation, resulting in workers being exposed to diesel particulate. The data was collected through personal sampling technique, where TC and EC data were recorded during their working shift.

1.2 PROBLEM DEFINITION

The safety of underground coal miners is a priority in the underground mining industry. The use of diesel engines in underground coal mine pose serious health effects to miners. Exposure to diesel particulate in diesel engines exhaust can potentially lead to serious health issues.

To provide a safe underground coal mine working environment in Australia, ensure miners' productivity increases and reduce health effects, it is important to review the DPM standards (the use of EC as DPM surrogate) used in Australia.

The current accepted industry standard practiced in Australia is 0.1 mg/m^3 EC, where EC is used as surrogate. The use of EC as a DPM surrogate is not as appropriate because TC also plays a key role in DPM. Therefore, it is appropriate that both are considered in DPM analysis. In this study, analysis of both EC and TC will be performed based on provided data to evaluate the compliance level of the current standard.

1.3 AIMS AND OBJECTIVES

The aim of the project is to investigate and review the Australian DPM standard for underground coal mines based on provided sets of EC and TC form Mine A underground coal mine. To achieve the aim of the project, the following objectives will be implemented:

- a comparison of different DPM exposure limits promulgate world-wide;
- a review of the current method and sampling techniques used to measure DPM in underground mining industry;
- an evaluation regarding difficulties in measuring DPM in underground coal mines;

- a review on health effects associated with DPM exposure;
- Provide available control technologies to reduce DPM concentration;
- An investigation on the compliance level of the provided data with the current Australian standard;
- An Analysis on the relationship between TC and EC; and
- Drawing conclusion based on the findings from the case study.

1.4 SCOPE

This study will investigate the compliance of the data collected to the current exposure standard practiced in Australia and analysing the relationship between TC and EC to evaluate the use of EC as surrogate for DPM. The results will be based on the data collected from Mine A underground coal mine, where the following proposed scope of the project is outlined in table 1 below.

Table 1.
Proposed Scope of the project

In Scope	Out of Scope
Comparing different exposure limits in different countries	Design of method in collecting data
Evaluation of current methods of measuring DPM in underground coal mine	TC and EC analysis for underground metal/non-metal
Understanding difficulties in measuring DPM in underground coal mines	Old DPM measuring techniques and dust measurement
Investigate TC and EC relationship	Coal and blank lung cancer issue
Risk involved in compiling of final report	Underground mine plan design
Critically analysing the data through TC/EC ratio	Mine site risk assessment

1.5 METHODOLOGY

This research study involves two components. The first component of these study is to conduct a literature review on diesel particulate matter. This literature review will cover background information of DPM and how it forms, review DPM exposure standard practiced in countries including Germany, Canada, USA and Australia, why DPM is difficult to measure in underground coal mines, health issues associated with DPM and control strategies used to reduce diesel particulate emission.

The second component is to obtain TC and EC data. This was conducted externally by the site supervisor at the Mine A underground coal mine. Personal sampling technique was used to collect the data. The data obtained will be used to generate results regarding the compliance level of the current standard and to generate a TC and EC relationship.

1.6 INDUSTRIAL SIGNIFICANCE

It is a prime requisite for any mining industry to provide a safer and healthier working environment for mine workers to ensure successful operation of the mine. This includes controlling the exposure of underground coal mine workers to DPM levels below 0.1 mg/m^3 EC. Due to the advance of DPM measuring techniques that can collect real-time measurement, the current exposure standard should be reviewed. Therefore, the findings of this project will assist in investigating the compliance level of DPM exposure in Australian underground coal mines.

Additionally, the findings of this study will provide insight into the mining industry and reassess the DPM standard practiced in Australia. In doing so, it will achieve the following:

- Establish a more effective and updated DPM standard;
- Provide a safer and healthier working environment for mine workers;
- Increase mine worker's productivity; and
- Reduce health effects associated with DPM.

2 DIESEL PARTICULATE MATTER

2.1 PARTICULATE MATTER

According to Belle (2008), DPM is defined as a sub-micron physical aerosol component of diesel exhaust, which is less than 1.0 micron and forms as the result of incomplete combustion of diesel fuels in diesel powered engines. The actual composition of DPM in diesel engines is a complex mixture, containing gaseous phase and particulate fraction.

The gaseous phase of the diesel contains gases similar to that of air, including nitrogen, oxygen, carbon dioxide and water vapour.

On the other hand, the particulate fraction of diesel aerosol consists of solid phase and semi-volatile organic compounds. The particulate phase contains very small particles, ranging from 15 to 30 nm in diameter and the particles has the ability to clump to each other forming clumps of particles. Regardless, the size of the clumps of particle is still below 1.0 micron.

The carbon component from diesel emission is made up of OC and EC, commonly known as TC. It accounts for 85% of the DPM (Belle, 2008). EC forms the basic building blocks of DPM and its pure carbon particles, whereas OC are complex carbon compounds found in DPM. The organic carbon includes hydrocarbon and aldehydes; however, it does not include inorganic compound such as sulphates.

The graphitic nature and increase surface area of the carbon particle enhance its tendency to absorb hydrocarbons from incomplete combusted diesel fuels, lubricating oil and compounds formed during combustion. Most of the particulate materials are made of different individual particles as can be seen in Figure 1.

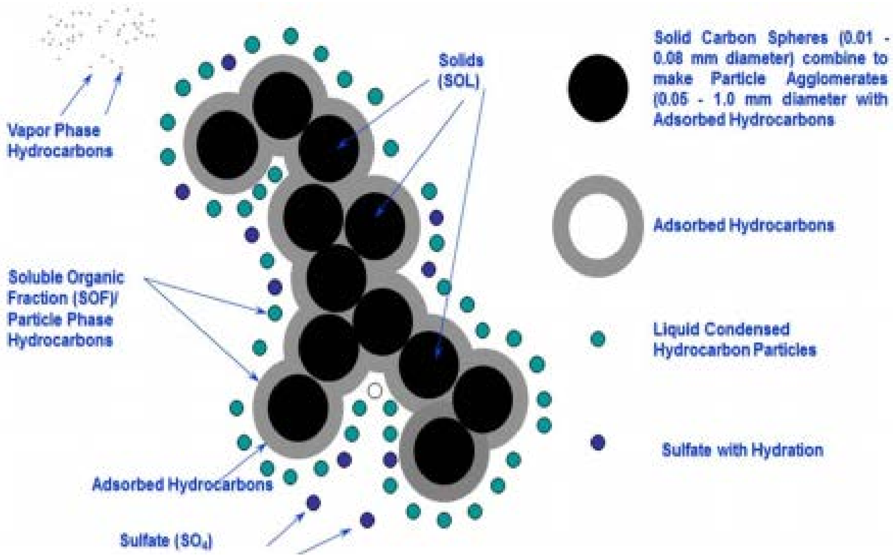

Figure 1. Typical systematic structure of particulate matter (Mohankumar and Senthilkumar, 2016)

2.2 PARTICULATE SIZE FRACTION

The particulate matter from diesel exhaust emission can be categorised under three different size modes. These include the nuclei mode, accumulation mode and coarse mode. Figure 3 below illustrate the diesel particulate size fraction. From Figure 2, it can be noted that the mass median diameter of diesel particulate is 0.2 μm and approximately 90 percent of the particles exist between 0.01 and 1 μm (USEPA, 2002). Due to the very small-sized nature of particles, they have the potential to reach deep into human lungs and cause serious health issues such as lung cancer.

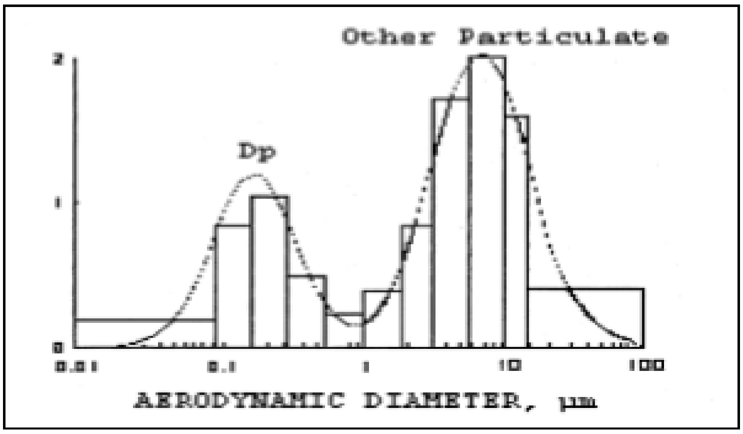

Figure 2. Diesel Particulate Size Fraction (USEPA, 2002)

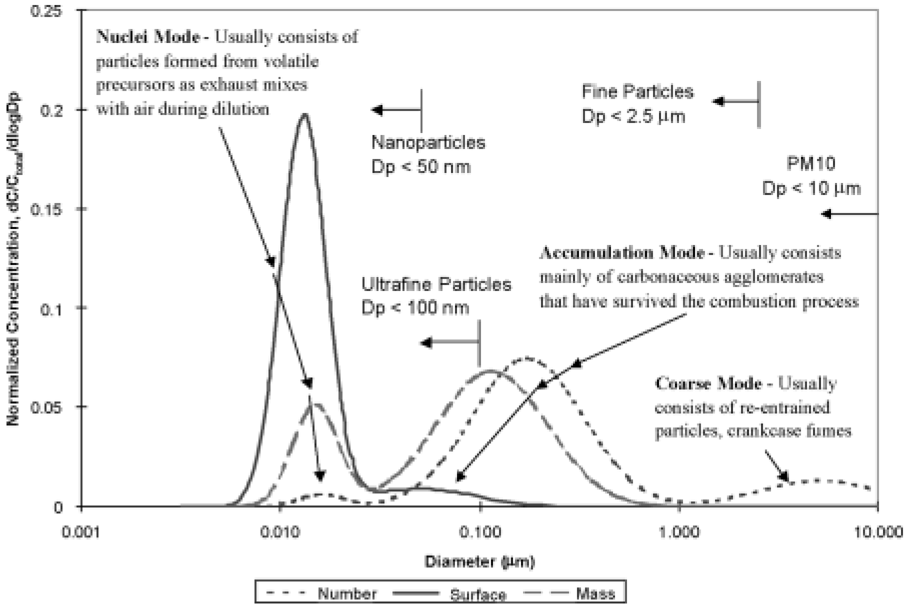

Figure 3. Diesel Particulate Modes (Jung and Kittleson, 2005)

The combustion process of DPM follows a lognormal and trimodal distribution model (Figure 3). The model shows that the concentration of any size of diesel particulate is proportionate to the area under the curve (Bagley *et al*, 2002). As such the size of diesel particulate for different modes are listed below:

- **Nuclei Mode**: Particle diameter ranges from 0.005-0.05 µm. Consists mainly of metallic compound, EC, volatile organics and sulphur compounds. The Nuclei mode contains approximately 1-20% particle mass of diesel particulate.

- **Accumulation Mode**: particle ranges from 0.05-0.5 µm in size. Consists mainly of carbonaceous agglomerates. These zone contains most of the diesel particulate mass.

- **Coarse Mode**: particle ranges from 0.5-1 µm and contains 5-20% of the total diesel particulate mass. Consists mainly re-entrained particles and fumes.

2.3 PHYSICAL PROCESS OF DIESEL PARTICULATE (SOOT) FORMATION

The physical formation of soot in diesel exhaust results from the conversion of liquid phase hydrocarbons and finally to gas phase. This conversion process involves six different steps, including: pyrolysis, nucleation, surface growth, coalescence, agglomeration and oxidations

(Mohankumar and Senthilkumar, 2016). A summary of the soot formation can be seen in Figure 4.

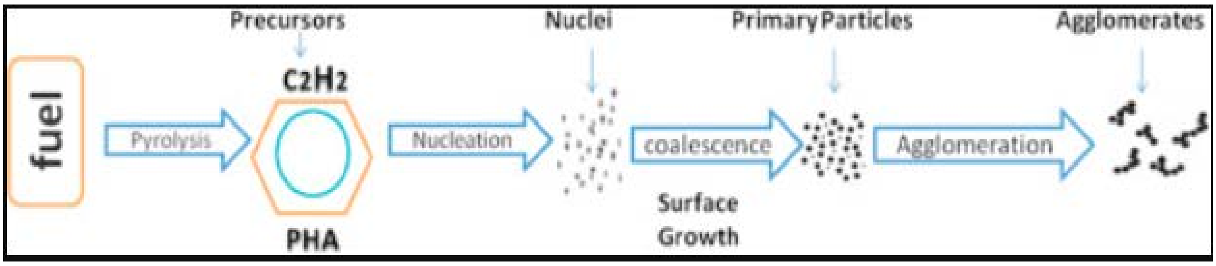

Figure 4. Systematic physical process of DPM formation (Mohankumar and Senthilkumar, 2016)

2.3.1 *Pyrolysis*

In the pyrolysis process, fuels are burnt at a high temperature and without a sufficient amount of oxygen. This results in a change to the fuel molecular structure. This reaction is endothermic and dependent on the concentration of oxygen and temperature. The pyrolysis of fuel initiates the formation of precursors, which are the building blocks of soot (Mohankumar and Senthilkumar, 2016).

2.3.2 *Nucleation*

In nucleation process, the reactants of the gas phase formed particles. The diameter of the nucleation ranges from 1.5-2 nm (Mohankumar and Senthilkumar, 2016). In a diesel cylinder, the initial number of soot nuclei is amounts to approximately 250 nuclei per cubic micrometre.

2.3.3 *Surface Growth*

The particles from the nucleation process forms a large pool of very small particles. The surface growth stage is responsible for the increase in soot mass, hence the size of the particulate matter increases in the surface growth stage. The rate of soot formation in this stage depends entirely on the number of nuclei present (Mohankumar and Senthilkumar, 2016). The surface growth rate increases for small size particles due to more surface area, while it decreases for large particle sizes.

2.3.4 Coalescence and Agglomeration

Coalescence and agglomeration is where different particles combine to form a single mass of particles. These single masses of particles inter-collide with each other resulting in agglomeration. Hence, the process decreases the number of particles present. However, it increases the size and mass. The size of the particulate depends on several factors including:

- Engine operating conditions;
- Sampling techniques;
- Hardware of an injector; and
- Methods of determining particle size.

2.3.5 Oxidation

The oxidation process involves the oxidising of carbon or hydrocarbon molecules to form soot during the combustion of diesel fuel. The process can take place at any time during the soot formation process. Its rate depends on the air-fuel mixture at the point of soot formation (Mohankumar and Senthilkumar, 2016). However, this process does not involve surface growth and the coagulation process. Once this process is completed in the tailpipe, the exhaust gasses cool down. Relatively low vapour pressure hydrocarbons, sulfates, other acids and bound water condense on the soot resulting in the formation of the diesel particulate matter.

2.4 POLLUTANTS ASSOCIATED WITH DIESEL EXHAUST

Most mining trucks are powered by diesel fuel. The diesel engines converts the chemical energy in the diesel fuel into mechanical power which it uses to power trucks and other machines. The reaction occurs within the engine cylinder where diesel fuel is injected at a higher pressure and mixes with air to produce power (mechanical energy). Illustrated in Figure 5, below, is a typical particle composition of a heavy-duty engine during the chemical reaction within a diesel engine.

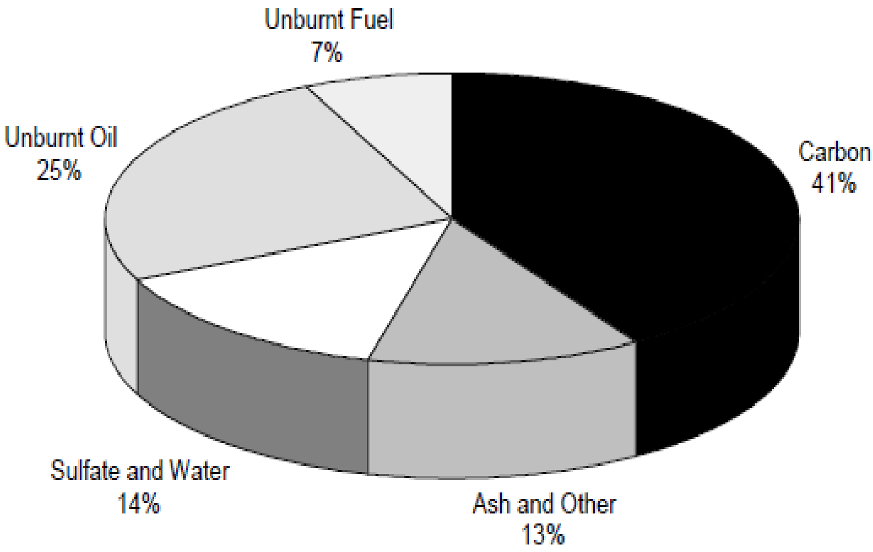

Figure 5. Particle composition of a heavy-duty engine (Burtscher, 2004)

The exhaust gas produced by incomplete combustion contains various constituents and is considered harmful to both human health and the surrounding environment. Each of the constituents will be discussed further below, as each are harmful contributors to human health and the environment. Provided in Table 2 is the typical output range of toxic material in diesel exhaust. The lower values are from new and clean diesel engines while the upper values are from older diesel engines.

Table 2.
Emission from diesel engines (Burtscher, 2004)

CO (vppm)	**HC (vppm)**	**DPM (g/m^3)**	**NO_x (vppm)**	**SO_2 (vppm)**
5-1500	20-400	0.1-0.25	50-2500	10-150

2.4.1 Carbon Monoxide (CO), Hydrocarbons (HC) and Aldehydes

CO, HC and aldehydes are generated as a result of incomplete combustion of diesel fuel. In addition to this, a significant amount of the exhausted hydrocarbon is derived from the engine lube oil. When engines operate in enclosed areas such as underground mines, the CO can easily accumulate in the ambient temperature, resulting in mine workers potentially experiencing headaches and dizziness. Furthermore, HC and aldehydes under the same conditions in underground can cause eye irritation and choking in workers. Both HC and Aldehydes are responsible for the characteristic smell of diesel fuel.

2.4.2 Nitrogen Oxides (NO_x)

NOx forms when nitrogen and oxygen react in the engine cylinder under high pressure and temperature conditions. Essentially, NOx consists mainly of nitric oxide (NO) and a small portion of nitrogen dioxide (NO_2). This constituent (NOx) is a very toxic compound which pose serious environmental issues because it plays a major role in the formation of fog.

2.4.3 Sulfur Dioxide (SO_2)

The diesel fuel contains sulfur, which generates SO_2 during the combustion process. The SO_2 concentration depends entirely on the content of sulfur in the fuel. This toxic chemical is colourless and releases an irritating odour, which is poisonous to humans. Furthermore, SO_2 is harmful to the environment as it is a major source of acid rain formation.

2.4.4 Diesel Particulate Matter (DPM)

Diesel particulate matter is a complex aggregate of both solid and liquid materials, which is discussed in detail in Section 2. It forms due to incomplete combustion of diesel fuels. Excessive exposure to this particulate matter over the standard exposure limit is considered hazardous due to associated health issues. Furthermore, it also has environmental impact if there is no proper mitigation plan to control the rate of emission.

3 INTERNATIONAL REGULATORY STANDARDS

3.1 SELECTION OF EXPOSURE STANDARD

The exposure limits of DPM have changed over past years due to availability of advanced measurement and monitoring systems, particularly in countries including the United States (US), Canada and Australia.

Monitoring with regards to DPM measurement, is described by Grantham (2001) as a process where series of measurement of airborne contaminants are conducted on exposed mine workers during their normal working shifts.

The two key components considered useful in the risk assessment of mine workers' exposure are a reliable estimate of exposure and a standard means of comparison. The second component which involves the workplace exposure standard is available for most of the contaminants. However, diesel particulates have been found a category that has no universally recognised exposure standard.

Considering the mining industry only Germany, Canada, USA and Australia have attempted to establish exposure standards. Provided in table 3 are some of the promulgated exposure standards used in the countries mentioned.

Table 3.
Diesel particulate matter exposure standards (Greiner *et al*, 2001)

Agency/Committee/Regulator	Date Submitted	Exposure Guideline/Limit	Substance Measured
Canadian ad hoc Diesel Committee (presently in effect in most Canadian mining provinces)	1990	1.50 mg/m^3	RCD
Mine Safety and Health Administration	2001	0.40-0.16 mg/m^3	TC
Switzerland, tunnelling	N/A	0.20 mg/m^3	TC
American Conf. Of Gov. Industrial Hygienists	1996	0.15 mg/m^3	TC
American Conf. Of Gov. Industrial Hygienists	1998	0.05 mg/m^3	TC
Germany, tunnelling	N/A	0.10 mg/m^3	EC
American Conf. Of Gov. Industrial Hygienists	2001	0.02 mg/m^3	EC

Table 4.
More Diesel particulate matter exposure standards (DieselNet, 2001)

Country or Organisation	Value, mg/m^3	DPM Measurand
Current Limits		
U.S: MSHA metal/non-metal underground mines [66 Fed. Reg. 5706 (2001)]	July 19, 2002: 0.4 January 19, 2006: 0.16	Total Carbon (EC+OC) as determined by the NIOSH meth 5040
U.S: MSHA underground coal mines [66 Fed. Reg. 5526 (2001)]	Emission rates set for various rates of equipment, e.g. heavy-duty equipment 2.5 g/hr	Total DPM measured in accordance with ISO 8178 procedures [30 CFR 7 (1996)]
Germany: General occupational environment	0.1	EC, coulometric
Germany: Underground metal and non-metal mining and construction sites	0.3	EC, coulometric
Canada: Underground, metal and non-metal mining	1.5	RCD
Switzerland [Majewski 1999]	0.1	EC, coulometric
Proposed Limits		
ACGIH [1995]	0.15	Particles < 1 µm in size
ACGIH [1998]	0.05	Total Carbon in particles < 1 µm in size
ACGIH [2001]	0.02 (EC = 40% of DPM)	EC particles < 1 µm in size

3.2 GERMAN STANDARD

The German mining industry adopted a pragmatic approach to implement their diesel particulate exposure standard. An exposure limit of 0.3 mg/m^3 EC was used for underground non-coal mines and other construction workplaces (Dahman, 2003). The exposure limit was based on the ‘Technical Rules for Toxic Substance System’.

However, for coal mines, the approach was practically tailored to a specified circumstance due to the issue of potential interference from coal dust. In such circumstances, operators calculate the particulate exposure from emission rates from vehicles and the ventilation airflow in the production area. Essentially, if the calculated exposure is greater than 0.3 mg/m^3 EC, the number of diesel engine operating in the same area should be reduced or increased the ventilation rate. However, there is a lack of information available regarding how the vehicle emission rate is calculated.

3.3 CANADIAN STANDARD

In Canada, the state governments promulgate the exposure standard, is similar to Australia. In such a case, the exposure standard is likely to vary. Most provinces in Canada use 1.5 mg/m^3 respirable combustible dust (RCD) as the exposure standard (Grenier, 2003). This exposure standard has remained constant since then. However, Grenier indicates that Quebec and Ontario used an alternative value, which 0.6 mg/m^3 RCD.

3.4 USA STANDARD

In the United States, the past exposure limit enforced by the Mine Safety and Health Administration (MSHA) was 350 µg/m^3 TC or 270 µg/m^3 EC (Belle, 2008). However, this was reviewed in 2008 and reduced to a final limit of 160 µg/m^3 TC, which is the current exposure limit for metal mines. Considering coal mines, there is currently no personal Occupational Exposure Limit (OEL) being enforced, but a laboratory test is performed and a limit of no more than 2.5 grams per hour of DPM is enforced.

Initially, in the United States, the MSHA considered TC as the appropriate surrogate for DPM because the particulate matter found in diesel exhaust contains 80 percent TC. However, after further investigation, it was found that using TC as the surrogate for DPM is inappropriate. This is because there are other sources commonly present in underground mines that can interfere with the TC analysis. Other sources of contaminants of EC and OC originated from mineral dust, oil mist and even cigarette smoke.

As such, the MSHA proposed to use EC as a surrogate for DPM. However, it also has its own downside where the EC fraction of the DPM can change depending on several factors including fuel type, engine type, duty cycle, engine maintenance, operator habits, use of emission control devices, and lube oil consumption (Winthrop and Watts, 2000). For instance, in a study performed by Burster *et al.* (2001), DPM from a sampled tailpipe has shown that the ratio of EC to the total mass ratio has ranged from 10% to 45%.

Ultimately, using TC or EC as a surrogate for DPM is not necessarily appropriate but rather both TC and EC should be considered in DPM analysis. Thus, MSHA used TC/EC ratio as exposure limits where it considers both TC and EC. Currently, the exposure limit used in the United States was based on the TC/EC ratio of 1.3. However, indications of using this TC/EC ratio of 1.3 at the final DPM limit of 160 $\mu g/m^3$ are still unclear.

The exposure limits enforced by the MSHA are based on beliefs that the limits are economically and technically feasible for mines but not necessarily based on health standards.

3.5 AUSTRALIAN STANDARD

In contrast to the US exposure limit where both EC and TC are considered in DPM analysis, Australia uses EC as a selective surrogate for DPM. The current accepted industry standard practiced in Australia is 0.1 mg/m^3 EC, measured in submicrons and a standard TC/EC ratio of 2. This exposure limit was first implemented by the New South Wales (NSW) Mineral Council in 1999 and has now been used in most Australian mines and workplace.

The Australian Institute of Occupational Hygienists (AIOH, 2013), due to the lack of more definitive data, supports the use of 0.1 mg/m^3 as the standard exposure limit for DPM. Essentially, AIOH believes that the current standard is balanced by minimising the effects of irritation and potential risk of lung cancer, and the standard limit is achievable as a best practice. Hedge *et al.* (2007) also state that considerable Australian research, conducted since the 1980s on control technologies to reduce diesel emission has provided sufficient information to support the current exposure standard of 0.1mg/m^3.

Additionally, other studies including that of Noll *et al.* (2005) suggest that the key reasons EC was used as surrogate is that EC is a major component of DPM, is very selective to DPM, and can be measured and sampled easily and accurately. AIOH (2013) also state that EC provides the best fingerprint of DPM emission, is stable and relatively free of interference.

Furthermore, if TC was to be used, the strategy of sampling would be complicated as interference would be an issue. It was also mentioned in Noll *et al.*'s studies that coal dust has less effects on EC results than TC. The factors discussed have led Australia and other countries to use EC as surrogate for DPM. However, this is unclear and a major area to be reviewed, particularly for underground coal mines in Australia.

Through a search conducted by Toxicology Excellence for Risk Assessment (TERA) (2014), they identified several occupational exposure guidance values applicable to DPM analysis in

Australia, as seen in Table 5. Contained in the table are the chemical types assessed, years they were assessed, guidance values, targeted populations and the sources of information.

Table 5.
Guidance value that is applicable to DPM analysis in Australia (TERA, 2014)

Organization, year	Chemical(s)	Name	Year	Guidance Value	Target Population	Source
Australia Department of Natural Resources and Mines (DNRM)	diesel particulate matter [measured as EC]	exposure limit	2012	100 µg/m^3 [8-hr TWA]	underground coal and metalliferous mines	http://mines.industry.qld.gov.au/assets/safety-and-health/safety-bulletin-127.pdf
Australian Institute of Occupational Hygienists (AIOH)	diesel particulate matter [measured as EC]	exposure standard	2007	100 µg/m^3 [8-hr TWA]	underground coal and non-coal exposures	http://www.aioh.org.au/downloads/documents/PositionPapers/AIOH_DieselParticulatePositionPaper.pdf
Western Australia Mining Industry Advisory Committee (MIAC, 2013)	diesel particulate matter [measured as EC]	acceptable limit	2013	100 µg/m^3 [8-hr TWA]	underground mines	http://www.dmp.wa.gov.au/documents/Factsheets/MSH_G_DieselEmissions.pdf
New South Wales Department of Primary Industries (NSWDPI) – Mine Safety (2008)	diesel particulate [measured as EC]	maximum workplace exposure standard	2008	100 µg/m^3 [8-hr TWA] *approximately equal to 0.16 mg/m^3 TC or 0.2 mg/m^3 diesel particulate	workplace exposure (mine atmosphere)	http://www.resourcesandenergy.nsw.gov.au/__data/assets/pdf_file/0011/419465/MDG-29.pdf

Given that 0.1 mg/m^3 EC is the exposure standard practiced in most mines in Australia, a TC/EC ratio of 2 is considered an appropriate baseline to investigate the compliance of data collected in Mine A coal mine.

However, it must be noted that the effectiveness of the current exposure standard in reducing the health risk regarding cancer is still unclear. This is due to the uncertainties involved in epidemiological studies.

4 EQUIPMENT AND SAMPLING TECHNIQUES TO MEASURE DPM

4.1 CURRENT MEASURING EQUIPMENT

There are various types of equipment employed to measure DPM, however, this section will focus mainly on some of the most common methods used recently. This includes the SKC Impactor system, and the two most recently developed DPM monitors, D-PDM and the FLIR Airtec.

4.1.1 SKC Impactor System – NIOSH ANALYTICAL 5040

The earliest approach to measuring airborne DPM was the SKC measurement approach and it focusses on shift average measurements (Belle, 2008). NOISH was involved in most of the DPM measurement instruments for more than 20 years.

The SKC approach is based on differentiating DPM from other respirable dust by implementing particle size selection. It is designed to sample atmospheres such as underground mines where it is very important to differentiate DPM from other respirable dust.

Essentially, the SKC DPM Cassette has a precise-jewelled impactor built inside the cassette which performs the differentiation of DPM. This is where the respirable dust with particle size of $\geq 1.0\mu m$ is screened out, leaving only DPM with $\leq 1.0\ \mu m$ particle size collected on the filter.

Collected samples are analysed using the NIOSH 5040 analytical method for EC and TC content. The SKC equipment is designed for one-time use only and it is always sealed during sampling to ensure sample integrity. The cassette contains different components, which is shown in Figure 6(b).

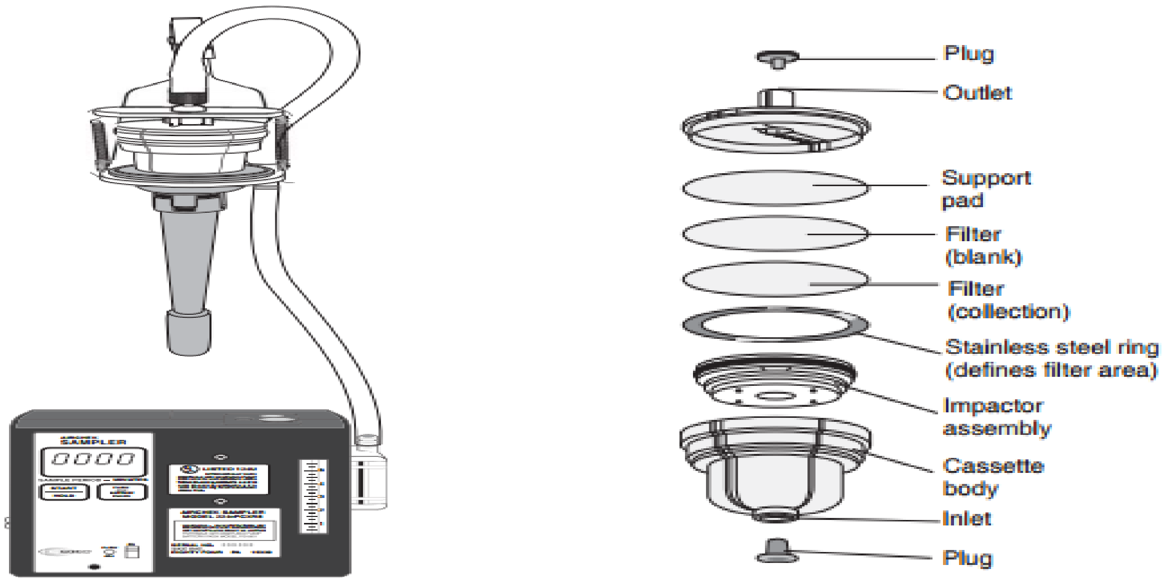

Figure 6a) (left): SKC impactor. b) (Right): Exploded components of SKC impactor (SKC limited, 2002)

4.1.2 D-DPM Method (First Real Time DPM Monitor)

D-PDM was the first real-time monitor for DPM, which is developed based on a successful real time Personal Dust Monitoring unit (PDM). The PDM measures the mine dust through a miniaturized direct mass sensor, which is contained in the DPM unit. However, changes were made to the PDM, converting it to D-PDM which enables it to measure DPM in underground mines.

According to Gillies and Wu (2008), the development of the D-PDM involves recognised laboratory testing and comprehensive series of underground mine testing. After successful laboratory testing and underground mine evaluation carried out in five operating mines, D-PDM was proved capable of accurately measuring DPM levels in a normal mine atmosphere.

During the D-PDM testing phase, SKC testing was also done, as it is the only other available approach in Australia. The result of EC and TC for both test is correlated, which demonstrates the validity of D-PDM monitor. This is a significant contribution to the mining industry because of its accuracy and real-time measuring nature. However, it must be noted that the results will vary from mine to mine depending on the conditions involved.

4.1.3 Flir Airtec

Flir Airtec is another real-time DPM measuring instrument that was commercially available in 2011 (Gillies *et al.*, 2014). Flir Airtec uses a laser scattering approach to measure the EC component of the DPM. The instrument consists of four main components, which includes a filter, impactor, pump and an optical measuring circuit. Each of the components have their own functions.

The impactor draws in air at a fixed flow rate to ensure that large particles are separated from the DPM. The mixed air/DPM then passes through a filter and the EC from the sampled air is collected onto a filter. Within the instrument is an optical sensing circuit that measures the intensity of the light transmitted through the filter from a laser source.

As more EC is collected in the filter, more light is absorbed. However, there is a drop in the voltage of the light sensor. This drop in voltage is used to relate laser absorption to the EC. A data logger records these changes and a microcontroller calculates the EC outputs.

Finally, the NIOSH 5040 analytical method is used to determine the specific amount of EC collected on the filter. Figure 7b) shows the Flir Airtec instrument, and on the left, is how easily this instrument can be fitted to a mine worker's belt.

Figure 7a) (lef: Flir Airtec device. b) (right): Personnel wearing the device

The instrument provides a real time measured results, which is very helpful in DPM analysis. Other advantages of this instrument are listed below:

- Lightweight, portable, and rugged design;
- Large LCD display;
- Can be easily fitted on miner’s belt loop or vehicle/wall mounted;
- Highly sensitivity to DPM;
- Contains a flow-selectable air pump;
- Provides results that is equivalent to NIOSH method 5040; and
- Long battery life operation.

4.2 SAMPLING TECHNIQUES

Due to the complex chemical and physical structure of the diesel particulate, health risk assessment of diesel particulate exposure is a difficult task. There are three sampling techniques commonly used to sample airborne diesel particulates. This includes size selective sampling, analytic choice and thermal analysis.

4.2.1 Size Selective Sampling

To implement a size selective sampling, there are two procedures of collecting samples involved - personal exposure and static sampling. Personal sampling is the most common technique used, where the sampling equipment is carried by the selected workers during their shift to record the quantity of DPM they exposed to (Figure 8). On the other hand, static sampling is used to determine the ambient DPM concentration that exists in the mine atmosphere in various locations.

Figure 8. DPM sampler worn by surface and underground LHD operator (Belle, 2008)

The strategy used to sample diesel particulate must address areas including selection of workers based on their type of duties and their job location, the time interval required to implement the sampling and also the number of workers available to sample. Practically, sampling of all workers will require a significant amount of time and money. Thus, implementing a flexible strategy is considered as best practice, and addresses the following areas:

- Sampling workers who experienced higher exposure risks. This includes operators of diesel engine equipment, diesel fitters, mechanics and other workers who work in an environment where diesel equipment is routinely operated;

- Sampling workers in different occupational groups. This will give a representative result for each group being sampled, which will assist in comparing the level exposure of different groups; and

- The time of sampling. This is also a critical area to be considered when sampling, which includes normal production and maintenance cycles. Additionally, the effect of seasons may also have an impact, therefore sampling should be done year-round (Grenier *et al*, 2001).

The concept of size selective sampling was investigated in detail by Cantrell and Rubow (1992). Both studies demonstrate that a bimodal distribution of aerosol average mass size in mining environments can be used to selectively sample diesel particulate from mine dust (Figure 9).

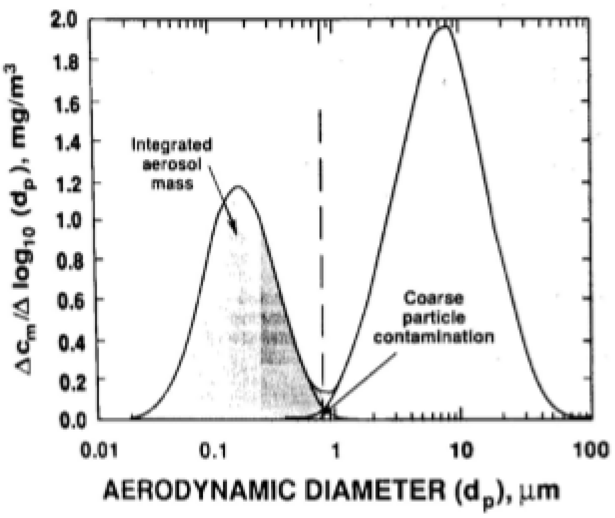

Figure 9. Size Distribution of Mine Aerosol (Cantrell and Rubow, 1992)

Both concluded that at approximately 0.8 μm separation of diesel particulate from mine dust can be achieved.

4.2.2 Analyte Choice (Carbon Speciation)

In analyte choice sampling, a surrogate for exposure is selected for sampling because the diesel particulate mixture is naturally complex. As such, carbon is the logic exposure surrogate because it makes up approximately 80 percent of the diesel particulate content. However, OG is less selective as it can be interfered by sources such as smoke, fumes and oil mists. Therefore, EC is always used as surrogate as it is a more selective measure of DPM (Birch, 2003).

4.2.3 Thermal Analysis

This method of sampling involves quantifying the magnitudes of EC and OG in a sample by utilising temperature and atmosphere control. Additionally, an optical feature is also used to correct pyrolytic generated carbon. The NIOSH 5040 method is the common technique used to determine carbon contents in the samples collected. A systematic set up of this system can be seen in Figure 10 below. The light from laser shown in red passes through the filter, which allow continuous monitoring of filter disturbances.

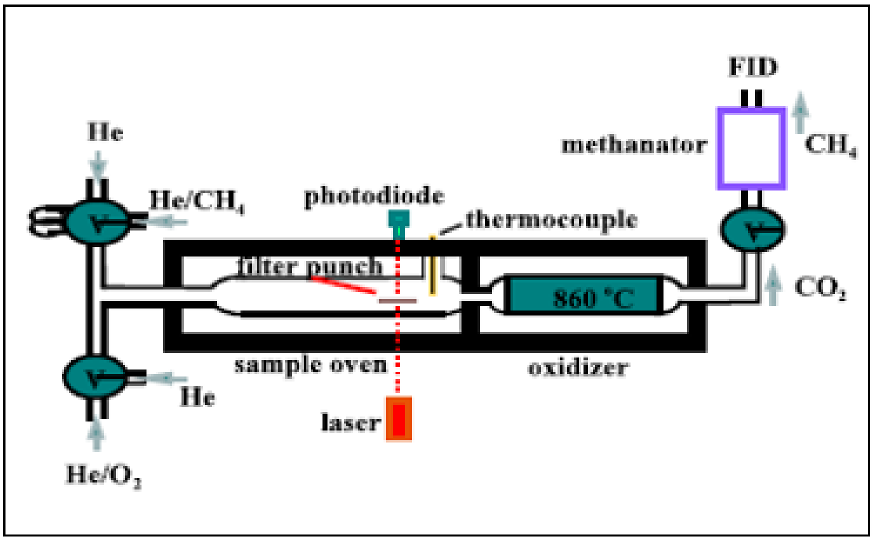

Figure 10. Systematic set up of NIOSH Method 5040 Analysis (Birch, 2003)

The NIOSH analysis process involves two stages. The first stage involves volatising the organic carbon and carbonate carbon from the sample in an atmosphere that contains pure helium. The temperature is increased in small increments up to a maximum temperature of approximately 870^{o} C (Figure 11). At the maximum temperature, the evolved carbon oxidises catalytically to CO_2 and further reduces to methane (Birch, 2003).

In the final stage, a pyrolysis correction is made and hence the EC can be measured easily. The temperature is reduced at this stage to allow a mixture of oxygen and helium to be injected, and, the temperature is raised again. The EC char is oxidised as oxygen is injected resulting in a concurrent rise in the filter transmittance. The correction of the char is accomplished once the filter transmittance reaches its initial value. The identified point is where the split between EC and OC occurs (Figure 11), and where EC is measured (Birch, 2003)

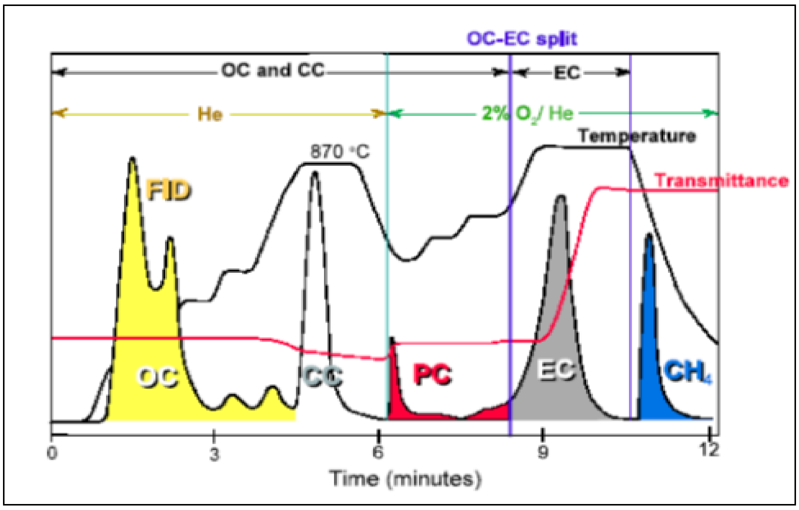

Figure 11. Typical Diesel Particulate Thermogram (Birch, 2003)

5 DPM IN UNDERGROUND COAL MINES

Mining operations, can involve either surface or underground mining. However, both of them utilise large trucks for hauling and loading material, as well as light vehicles to transport personnel. Diesel engines mostly power this equipment.

The increased use of diesel-powered engine in the mining industry has been evident in both US and Australia. A study performed by MSHA in the US shows that 18 percent of the 971 coal mines and 78 percent of 261 underground metal/non-metal mines use diesel engines (Federal Register, 2001). Similarly, most mines in Australia utilise diesel-powered trucks in their mining operations.

The use of diesel engines is an issue in enclosed environments, particularly in underground mines. This is because the particulates from exhausts and gases can accumulate if there is a lack of proper ventilation and monitoring system installed in underground mines. As such, underground mine workers are more exposed to DPM compared to other working places. Based on a study by Cohen *et al*. (2010), the study shows that exposure of underground mine workers is one to two orders of magnitude higher than normal truck drivers and those working in railway roads.

In underground coalmines, higher DPM concentration was found in haulage ways and areas where various diesel-powered engines operate. Furthermore, where there is more equipment operating and less airflow is experienced. The concentration level of DPM in underground coal mines depend mainly on the following factors:

- The amount, size, and workload of diesel powered equipment;
- The rate of ventilation; and
- The effectiveness of control technology used.

There have been several studies carried out in Australian underground mines. One of which was presented by Hedges *et al*, (2007) in the AusIMM New Leaders conference in May 2007. This paper stated that there are nine underground mines participating in a baseline exposure monitoring survey where most underground workers are being sampled using personal exposure monitoring. The results are shown in Figure 5, where people that operate, and are in close contact with diesel-powered engines, are more exposure to DPM compared to others.

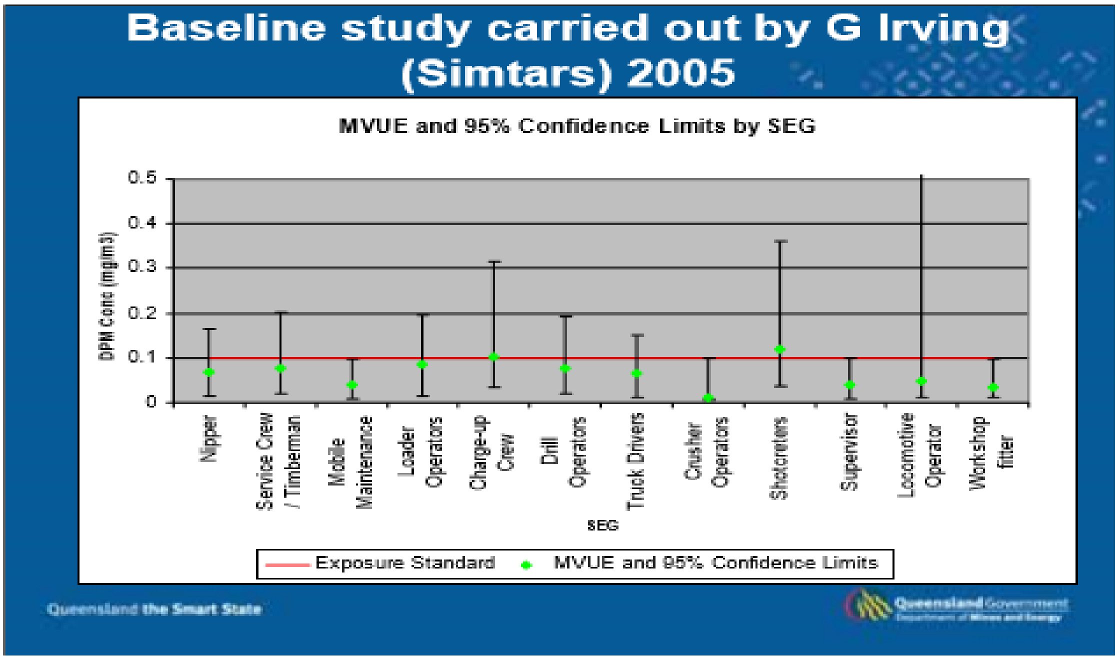

Figure 12. Baseline study on personal working in underground coal mine (Irving, 2005)

The green dots are the estimated mean concentrations of DPM and the red line is the exposure standard used in Australia. From Figure 12, it can be seen that charge-up crews, shotcretes, drill operators and loader drivers (production workers) experience the highest exposure to DPM.

However, there is difficulty in measuring DPM concentration in underground coalmines due to interference from coal dust, oil mist and smokes from cigarettes.

5.1 DIESEL POWERED EQUIPMENT IN UNDERGROUND COAL MINES

Most of the mining industry use diesel powered equipment because they believe that it has productivity and safety advantages over equipment powered by other sources. As stated by Federal (2001), the first diesel engine was developed by a German engineer Rudolp Diesel. It was modified to burn distillate petroleum (diesel fuel), which is now commonly used in mining industries.

Most of the diesel engines used in underground coal mines are utilised to power support equipment and not production equipment. On the other hand, diesel engines used in underground metal/non-metal mines are utilised mainly for loading and hauling operations.

Furthermore, the average engine power used in underground coalmines for coal loading and hauling is less compared to those used in underground metal and non-metal mines. This is because of the constraints in space as well as other operating conditions often encountered in underground coal mines.

However, engines used in underground coal mines can be classified under three categories: permissible diesel equipment, heavy-duty non-permissible and light-duty non-permissible diesel equipment.

5.1.1 Permissible Diesel Equipment

Permissible diesel equipment is equipment considered safe to operate in underground coal mines where methane gas is present in higher concentration (Federal Register, 2001). The permissible diesel powered equipment used in underground coalmines are provided with special equipment to prevent ignition from methane. The special equipment includes flame arresters as well as special treatment of joints and flanges.

In general, permissible diesel equipment is used where coal is mined, because methane is liberated during the process. Such areas are commonly known as “in-by” areas. However sometimes, they are used in return air courses. Due to the special equipment used to protect ignition, the permissible diesel equipment is safer to use in underground coal mines.

The permissible diesel equipment generates a significant amount of DPM concentration in the underground coalmines where they are operating. This is because the equipment has large engines, increased workloads, are often found in areas far from ventilation sources, and are close in contact with mine workers.

5.1.2 Non-Permissible Diesel Equipment

Non-permissible Diesel equipment is used in underground coal mines where methane concentration is less or can be controlled through ventilation (Federal Register, 2001). Most of the equipment used in underground coal mines are in this equipment category and are generally operated in areas away from the coalface, commonly known as “out-by” areas.

Non-permissible equipment is also classified as heavy-duty diesel-powered equipment and low-duty diesel powered equipment. Heavy-duty equipment includes those that fall in the following classifications:

- Equipment that cuts and moves material (rock or coal);
- Equipment that operates drilling and bolting;
- Equipment that transports longwall components; and
- Self-propelled diesel fuel transportation units.

On the other hand, light-duty diesel equipment is those that does not fall in heavy duty equipment criteria. This includes light vehicles used to transport personnel and other products from surface to underground mines.

As the name suggests, heavy-duty diesel equipment performs considerable amount of work compared to light duty vehicles. As such, it also implies that there is considerably more DPM concentration emitted by heavy-duty equipment than light duty vehicles.

5.2 DIFFICULTIES OF MEASURING AMBIENT DPM IN UNDERGROUND COAL MINES

MSHA believes that while various methods can measure high ambient DPM concentration in underground coal mines with reasonable accuracy, they cannot provide similarly accurate ambient DPM measurements at lower concentration.

Essentially, the available methods have potential difficulties in differentiating the DPM particle sizes from coal mine dust. The use of an impactor assists to distinguish the large particles from submicron particles. However, certainty on how much fine particles from DPM and coal dust reaching the sampler is a major issue encounter in underground coal mines.

According to Federal (2001), to solve the differentiating issue analytically, the NIOSH 5040 method has to be adjusted to allow measurement of EC only. However, there is no relationship established between concentration of EC and total DPM under different operating conditions. Since the amount of OC of DPM varies with types of engines and duty cycles, the total DPM present for a given amount of EC is expected to vary accordingly. As such, the accuracy and consistency of measuring ambient DPM at lower concentration remains an issue in underground coal mines.

5.3 HEALTH EFFECTS ASSOCIATED WITH DPM EXPOSURE

Rising levels of adverse health effects from exposure to diesel particulate matter has been a major subject of discussion among different health organisations worldwide over the past decades, and an ongoing area of research in the present. There have been significant studies conducted on both animals and human in relation to health effects from DPM exposure. A review of the findings of some major Health Organisation studies are discussed here-in.

A study presented by NIOSH (1988) proposed a potential relationship between lung cancer and exposure to diesel emission. The finding was based on toxicological studies in rats and mice. However, there is limited epidemiological evidence to support the proposed relationship. Similarly, International Agency for Research on Cancer (IARC, 1989) animal studies show sufficient evidence regarding carcinogenic risk but limited evidence concerning humans. This has brought further attention to other health institutes to undertake intensive epidemiological studies.

The Health Effects Institute (HEI, 1995) were involved in 30 epidemiological studies from 1950 to 1980, where workers exposed to diesel emissions were investigated. Half of the studies showed an increase in risks of lung cancer while the other half showed no risk. After carefully examining the outcome of the study, they concluded that the investigation showed a weak relationship between exposure to diesel exhaust and lung cancer. However, caution has been made that the studies lacked proper exposure data for the whole population and disregarded the influence of tobacco smoking among the studied population.

Mine Safety and Health Administration (MSHA, 2001) stated that there is some degree of certainty in the relationship between occupational exposure to DPM and lung cancer. This was based on a review of 47 epidemiological studies where 41 showed some degree of association. However, there is limited statistical power to support the outcome. As such, MSHA concluded that over a period of 45 years, the exposure mean concentration of 0.64 mg/m^3 had a relative risk level of 2.0 for lung cancer.

In Australia, the New South Wales (NSW) coal industry was involved in a large-scale investigation into cancer risk, which was completed in 1994 and later updated in 1997. The investigation involved matching the medical records of NSW coal industry employee with the records of the NSW Central Cancer Registry. The investigation found that the overall cancer incidence ratio was less than the general population. Considering lung cancer, the rate was found to be less than the normal rate (Brown *et al* 1997).

In 2001, a study by MSHA (2001) has indicated their support of diesel particulate as a potential carcinogen. Furthermore, it was stated by the joint coals board that diesel particulate could be cancer causing, similar to the risk level of a passive smoker.

The United States Environmental Protection Agency published their health assessment for diesel engine exhaust in May 2002 (USEPA, 2002). The assessment aimed to characterise human health hazards of diesel exhaust and to determine the degree of association between exposure to DPM and response of disease. Their findings enabled them to conclude that DPM is characterised as the most appropriate parameter to correlate with human health until more information, including mechanism of toxicity and mode of action, are available. Regarding health effects, US EPA (2002) suggested that the health effects of DPM fall into three categories. These include:

- **Acute Effects;**

  Acute effects include eye, throat and bronchial irritation, light headedness, nausea, cough and phlegm.

- **Chronic Non-Cancer Respiratory Effects; and**

  Based on animal studies they suggested that there is potential for health effects relating to chronic respiratory diseases in humans.

- **Chronic Carcinogenic.**

  The US EPA also concluded that lung cancer was evident in occupationally exposed groups and at low environmental exposure, it is considered as a hazard.

With the intensive research involved in the health effects relating to DPM, many regulatory authorities in the USA, Europe and Canada concluded there is sufficient evidence to suggest that DPM has the potential to cause lung cancer. However, quantification of potency will still be an area that requires collaborative debate on. With this scientific uncertainty, policy of caution has been adopted by man organisations to minimise exposure of employee to DPM.

Adoption of the caution strategy was also implemented in most underground coal mining industries in Australia, where positive results have been achieved. Positive results include a reduction in employee irritant effects and an increase in employee productivity. However, the issue of lung cancer remains unclear.

6 CONTROL TECHNOLOGIES

6.1 INTRODUCTION

Controlling diesel particulate from diesel-powered engines in underground mining industry has been a significant challenge. In the past, the focus of the mining industry was to control gaseous emission through proper ventilation design, implementing workplace occupational exposure standards and installation of gas monitoring systems.

It was not until the early 1980s when NIOSH (1988) studies showed that potential health effects associated with diesel particulate. This prompted the investigation of control technologies.

According to Schnakenberg and Bugarski (2002), a review of available control technologies was released by the NIOSH. The review contains control technologies that have the potential to control diesel emission in underground mining industry. The aim of the paper was to investigate and provide information regarding the performance and limitations of available control technologies to reduce diesel exhaust. Most of the discussed control technologies used in underground coal mines discussed include the following:

- Low emission engines;
- De-rated engines;
- Fuels & fuel additives;
- Catalytic converters;
- Particulate filters; and
- Maintenance.

Discussed here-in are areas that perhaps require intensive focus from the mining industry to control the issue of diesel particulate emission. This includes fuel quality, ventilation, exhaust treatment device, engine de-coking, engine design and maintenance. In Mohankmar and Senthilkumar studies, they recommended that particulate matter can be reduced through a comprehensive pre-combustion and post-combustion control strategy, which is summarised in Figure 13.

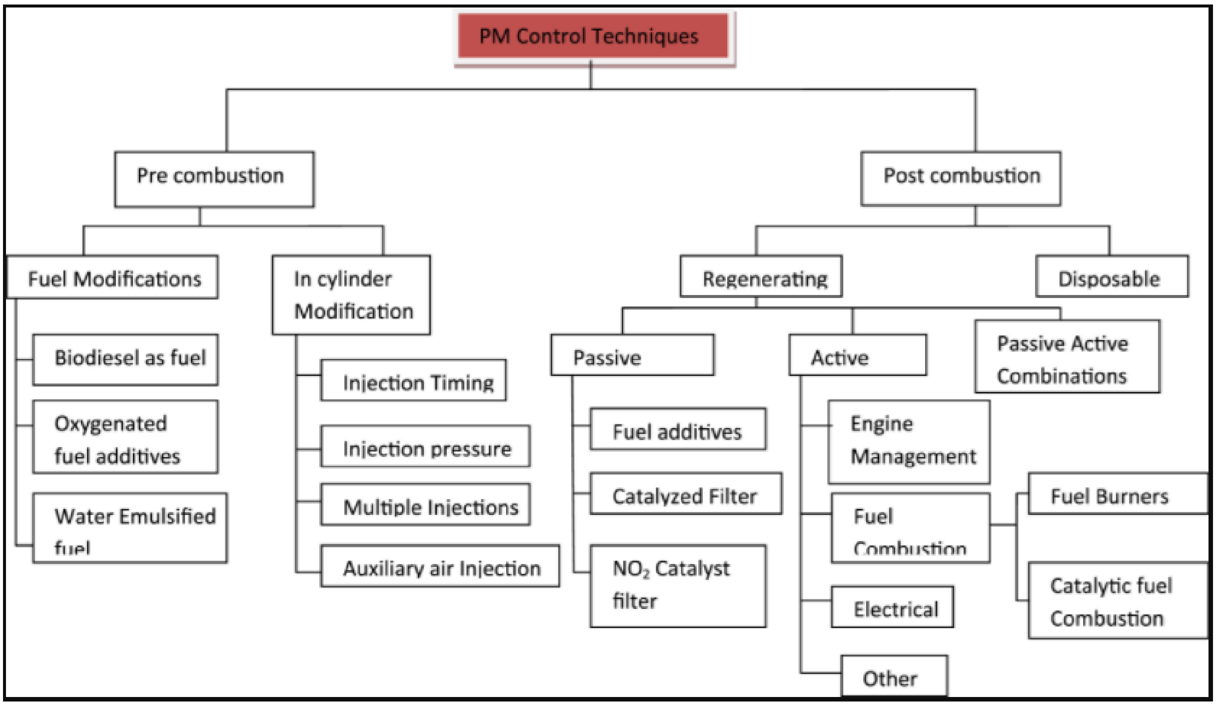

Figure 13. DPM pre-combustion and post-combustion techniques (Mohankumar and Senthilkumar, 2016)

6.2 Fuel quality

Fuel quality is considered the most investigated parameter, as improving fuel quality would resolve the issue of particulate generation. The fuel itself has different characteristics that determine the quality of fuel. Ryan *et al* (2000) summarised the fuel properties believed to generate exhaust particulates. These include fuel viscosity, boiling range, fuel specific gravity, hydrogen content, aromatics and cetane number. However, the influence of sulphur content on fuel quality was not mentioned in this document.

Ullman (1989) discovered that sulphur content has potential to influence the quality of fuel. In his investigation, the effects of sulphur content, aromatics, boiling point and cetane numbers were investigated. The investigation showed that by reducing the fuel sulphur content, the level of diesel particulate also reduces, whereas an increase in the cetane number results in reduction of hydrocarbons, carbon monoxide, nitrogen oxides and diesel particulates.

Similarly, in Graboski's (1992) research on fuel quality, he concluded that by controlling sulphur content, cetane number and atomic content of fuel, the level of particulate generated from exhaust would be reduced up to 25 percent.

There have been several studies undertaken within the Australian coal mining industry on fuel quality with varying conditions that have shown diverse results. In Robinson *et a*l's (1990) research, he found that there is a significantly large amount of "soot" produced from Australian diesel fuel than US fuels. He believes that this is because of the higher aromatic content and higher boiling point used in Australian fuel. In Pratt *et al*. (1997), earlier research on the relationship between fuel quality and diesel particulate was inconclusive. This is because of errors involved in the sampling and analysing method used. However, he later reviewed his research and found that was a reduction in particulate level. In Humphreys *et al.* (1998) research, it was concluded that the density of fuel affects the generation of diesel particulates.

Despite the diverse conclusion on fuel quality, the NSW Minerals Council (1999) recommended that the mining industry should consider utilising diesel fuel with low sulphur content. This recommendation has been implemented as a controlling strategy in most of the mining industry around Australia.

6.3 VENTILATION

Ventilation has been widely used in the underground mining industry to remove contaminated air and provide fresh air to underground mine working areas. Ventilation has been considered as way of controlling diesel particulate accumulation in underground coal mines. As such, the establishment of standards on air quantities have been prescribed.

The statutory ventilation rate in the United States is determine through approval from the Mine Safety and Health Administration. A standardise test cycle has been implemented to ensure the amount of air required is capable of reducing the exhaust concentration to the recommended threshold limit. However, allowance has to be made for the quantity of air for each engine operating in different sections of the mine. While ventilation is seen as an adequate way to control gaseous emission, there is an issue regarding the quantity of air required to control diesel particulates.

A study performed by Pratt *et al* (1997) demonstrated that large diesel engines operating in underground confined areas with minimum airflows often result in thermal stratification. As such, accumulation of diesel particulate matter is often concentrated approximately one third of the upper roadway height.

The NSW Mineral Council suggested a vehicle control system where restriction on the number of trucks entering a section of the mines is seen as effective. This is to limit the concentration of diesel particulate with the assumption that it can be easily ventilated in low concentration. The NSW coal mining industry later recommended that for underground coal mines with diesel engines, the required ventilation rate should be 0.06 m^3/s/kW or 3.5 m^3/s.

The approach used in the United States was unique where a “Particulate Index approach” was implemented. The particulate index value represents the quantity of air that is required to reduce the level of diesel particulate to 1 mg/m^3 (MSHA, 1996). Furthermore, the index approach is also utilised to develop ventilation design for mines.

However, there are still area for improvements to fully understand the relationship between ventilation and diesel particulates.

6.4 EXHAUST TREATMENT DEVICE

There has been extensive research and development of exhaust treatment device conducted over the past years. One of the earlier devices is the catalytic converter. The catalytic converter is renowned for its effectiveness in reducing carbon monoxide levels in diesel exhausts (Holz, 1960).

A joint industry-government working group performed further investigation on catalytic converter and scrubber to evaluate their effectiveness (NISOH 1982). It was found that using the catalytic converter, there was a significant reduction in hydrocarbons, carbon monoxide and odour. However, there was no virtual reduction in particulates or oxides of nitrogen. Considering scrubber tanks, there was an approximate 30 percent reduction in carbonaceous particulates but no reduction was observed for carbon monoxide and oxides of nitrogen. Pratt *et al* (1995) and the NSW Department of Mineral Resources (1999) concluded that the use of water baths is effective in reducing particulates from raw exhaust. As such, NSW coalmines considered water bath as one of their statutory options where vehicles are fitted with such device.

In the United States’ and Canada’s metal/non-metal mines, ceramic wall flow particulate filters were commonly used (Waytulonis, 1992). However, the exhaust temperature of the equipment, exceeding the required temperature of 150 degrees Celsius, excluded them from use in underground coal mines. This is because of its potential to cause ignition.

Despite the exclusion of a regenerative exhaust filter in underground coal mines other approaches were also investigated. Such include that of Mogan and Danity (1987), where a venturi-water scrubbing system was investigated. Their investigation showed that the level of particulates was reduced by 65 to 75 percent. Another device that was reported by Ambs and Hillman (1992) is the low temperature post scrubber tank disposable filter. This device was capable of reducing diesel particulate matter in mine atmosphere at by 93-98 percent. However, the life of the filter only lasts for up to 10 hours. Furthermore, Ambs stated that there is a safety concern with the device as the filter was made of paper and therefore has the potential to cause ignition if the system fails, resulting in an increase in temperature. As such, paper filters are not recommended to be used unless there is a proper shutdown system. A systematic layout of how diesel particulate filters operate can be seen in Figure 14.

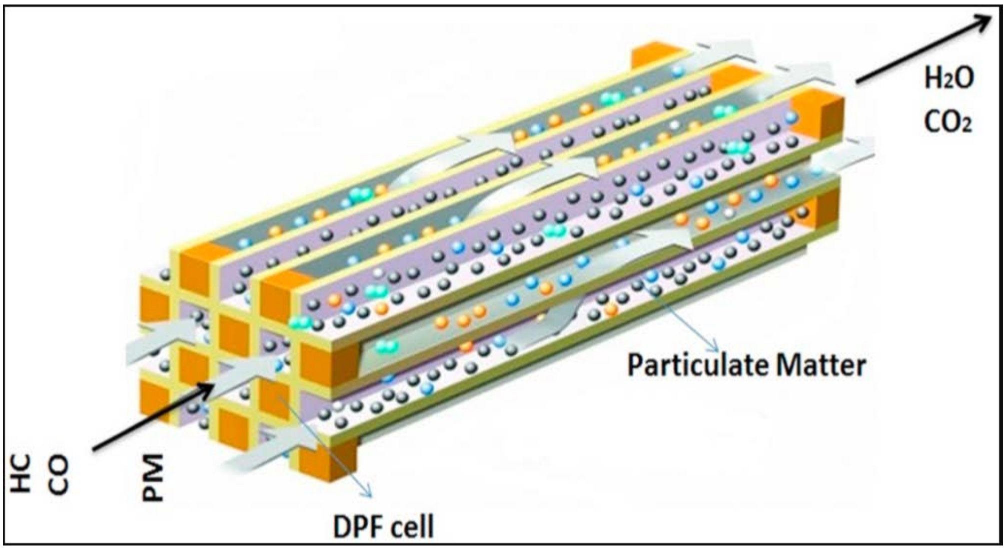

Figure 14. Diesel particulate filter mechanism (Mohankumar and Senthilkumar, 2016)

Due to the issue with the usage of paper filter, Pratt *et al* (1997) developed a new concept by using polypropylene material. This material melts at 170^{o} C and it is not subjected to degrade from water presence. However, it does not support combustion. This concept has indicated reduction in particulate level and is commonly used in NSW coal mining industry.

Lowndes and Moleney (1996) reported on exhaust dispersion device that was used widely in mining industry. This device only dilutes the raw exhaust emission but does not remove the amount of diesel particulates in the mine atmosphere.

6.5 ENGINE DECOKING

Another approach is the use of decoking chemical agents to reduce diesel particulate emission (Pratt *et al*, 1997). The approach involves injecting decoking agents into the engine while it is operating and within 30-45 minutes, the chemical detaches coke build-up within the cylinder resulting in better combustion. This has a positive outcome in the reduction of diesel particulate generation and its effectiveness lives up to 10 months before re-coking can be carried out again.

6.6 ENGINE DESIGN AND MAINTENANCE

Probably the two most areas that have the greatest influence in reducing diesel particulate are engine design and maintenance.

Waytulonis (1992) undertook a comparison study between a normal functioning diesel engine and an electronic controlled engine, both tested under the same conditions. It was found that the electronically controlled engine reduced the level of diesel particulate emission at approximately 50%, which is comparably higher than the normal engine. This was achieved through optimising fuel injection timing so that the rate at which fuel was injected matched the power requirement.

Most of the new designs involving electronically controlled engine are used mainly in the metalliferous mining industry. However, in the coal mining industry, such designs are not permitted due to safety issue regarding ignition. As such, coal mining industry continues to utilise the normal aspirated engines.

Regarding poor engine maintenance and its effect on diesel emission, Waytulinonis (1992) demonstrated how restriction on air intake and over fuelling could affect the diesel particulate being generated. He restricted the air intake at 13 kPa, over fuelled the engine by 20%, and found that the particulate generation increases significantly. He then concluded that the increase in particulates in a single fault could have arisen from intake restriction and over fuelling.

Davies (2000) undertook an investigation into the effect of maintenance on diesel emission on an engine operated in the NSW coal industry. He measured the total carbon prior to the maintenance of the engine, which he recorded was 0.84-1.4 g/kWhr. After the maintenance, the same load condition was applied and the TC was re-measured. He found that it reduced by approximately 55-71%. This indicates the effect of maintenance on diesel particulate emission.

To minimise the generation of diesel particulate, MSHA (2003) recommended guidance on the maintenance of diesel equipment, which includes the following:

- Ensuring the correct fuel injection rate and timing is used;
- Fuel injection systems are operated correctly; and
- Clogged air filters and leaks in the air intake system and high oil consumption.

7 CASE STUDY

7.1 INTRODUCTION TO GRASSTREE COAL MINE

Mine A is an underground coal mine that is located close to the town of Middlemount, in the Bowen Basin Coalfield of Central Queensland (Figure 15). Mine A has an estimated underground mining coal inventory of approximately 770M tones, with a total reserve of 60M tonnes of coal. This coal mine produces quality hard coking coal for export to countries including North Asia, Europe, India and Brazil.

Figure 15. Location of Mine A (Bruggemann, 2002)

7.2 GEOLOGY AND STRATIGRAPHY

Mine A coal mine is based on coal reserves in the German Creek coal formation and Rangal coal measure, which have low to medium volatile hard coking coal (Jakeman, 2001). Mine A mined most of its coal from the German Creek Formation, which consists of five different coal seams including; German creek, corvus, tieri, Aquila and Pleidseams (Figure 16).

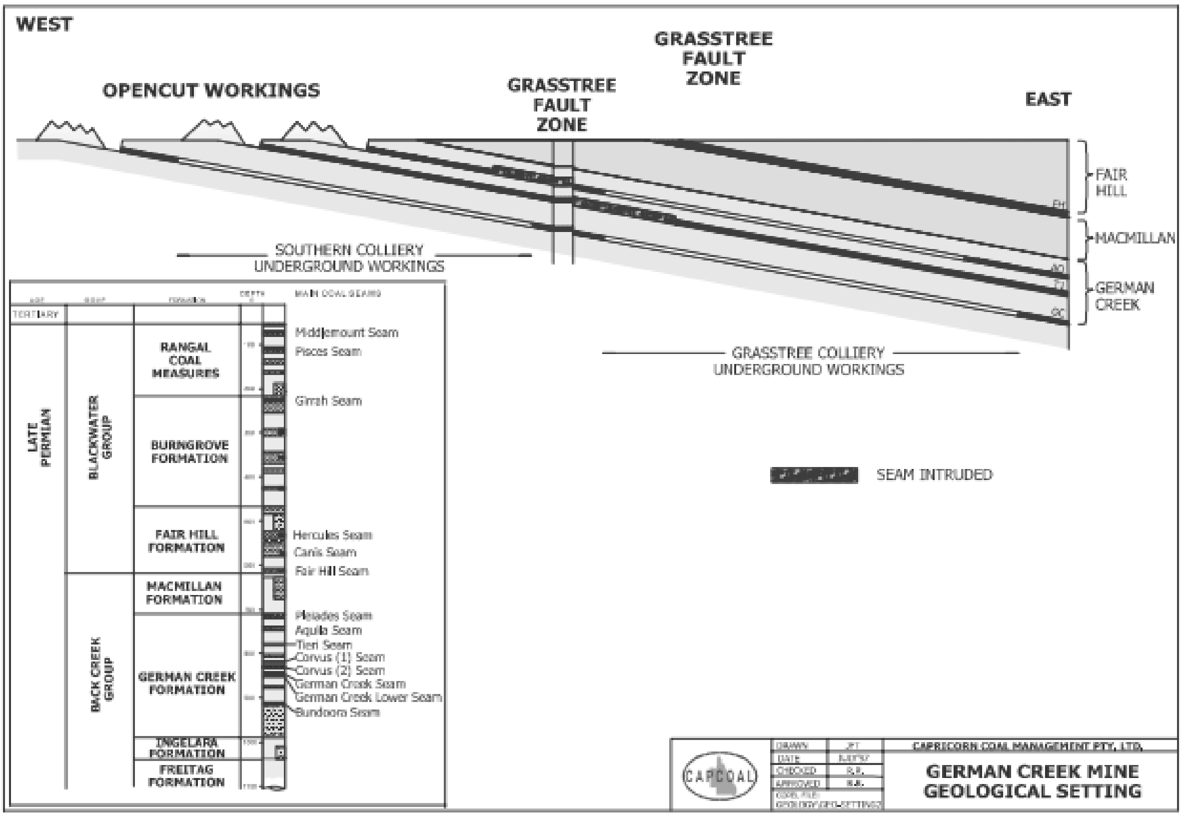

Figure 16. Geological Setting of German Creek Mine (Jakeman, 2001)

Mine A coal mine is situated in the centre of the Bowen Basin where their operation covers a 12km strike length. The German Creek group of seams has strata that contains hard, well lithified, claystones, sandstone and siltstones (Jakeman, 2001). The coal seams’ thickness ranges from 0.5m to 4m (Figure 17).

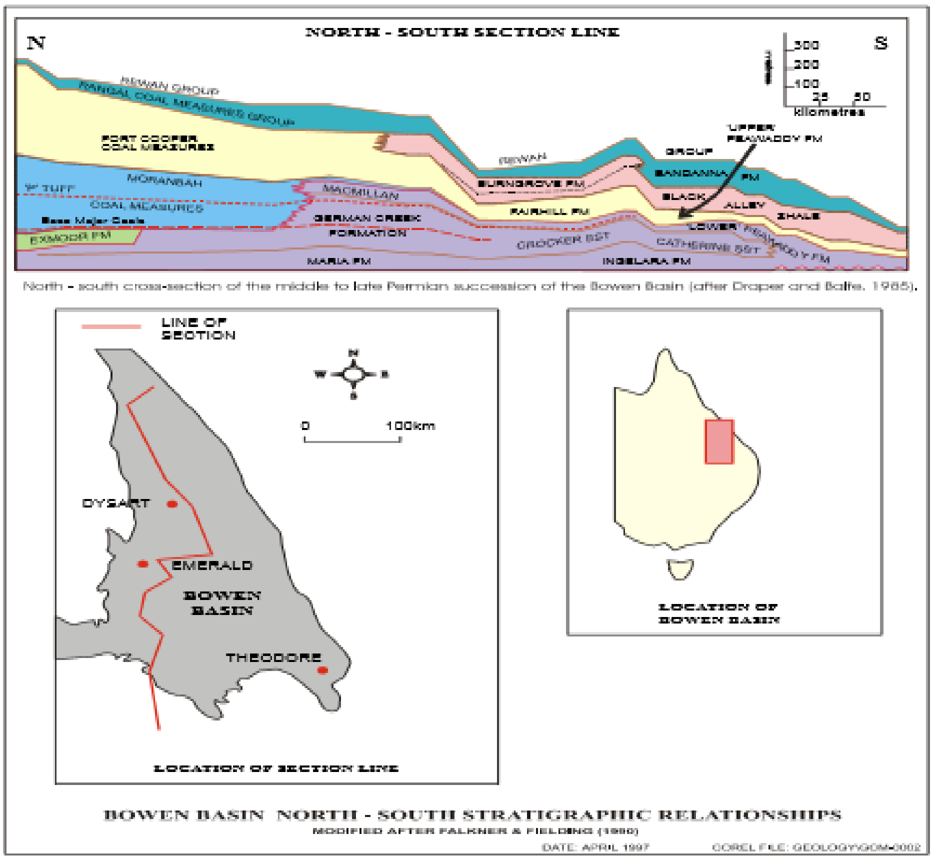

Figure 17. Bowen Basin North – South Stratigraphy (Bruggemann, 2002)

7.3 Mining

Mine A mining operations utilises the underground longwall mining method to extract coal with four continuous miner developments (Figure 18). The mining depth of the operation varies from 220m to 400m. Mining of the German Creek seam commenced in 2003 with development of gateroads, which focus mainly on 800 longwall panel series (Figure 18). However, the longwall extraction actually commenced in 2006. The seam currently mined is the upper German Creek seam, which is approximately 2.6m to 3.1m thick (Colwell *et al*, 2008). The current mine life of Mine A is expected to end in 2019.

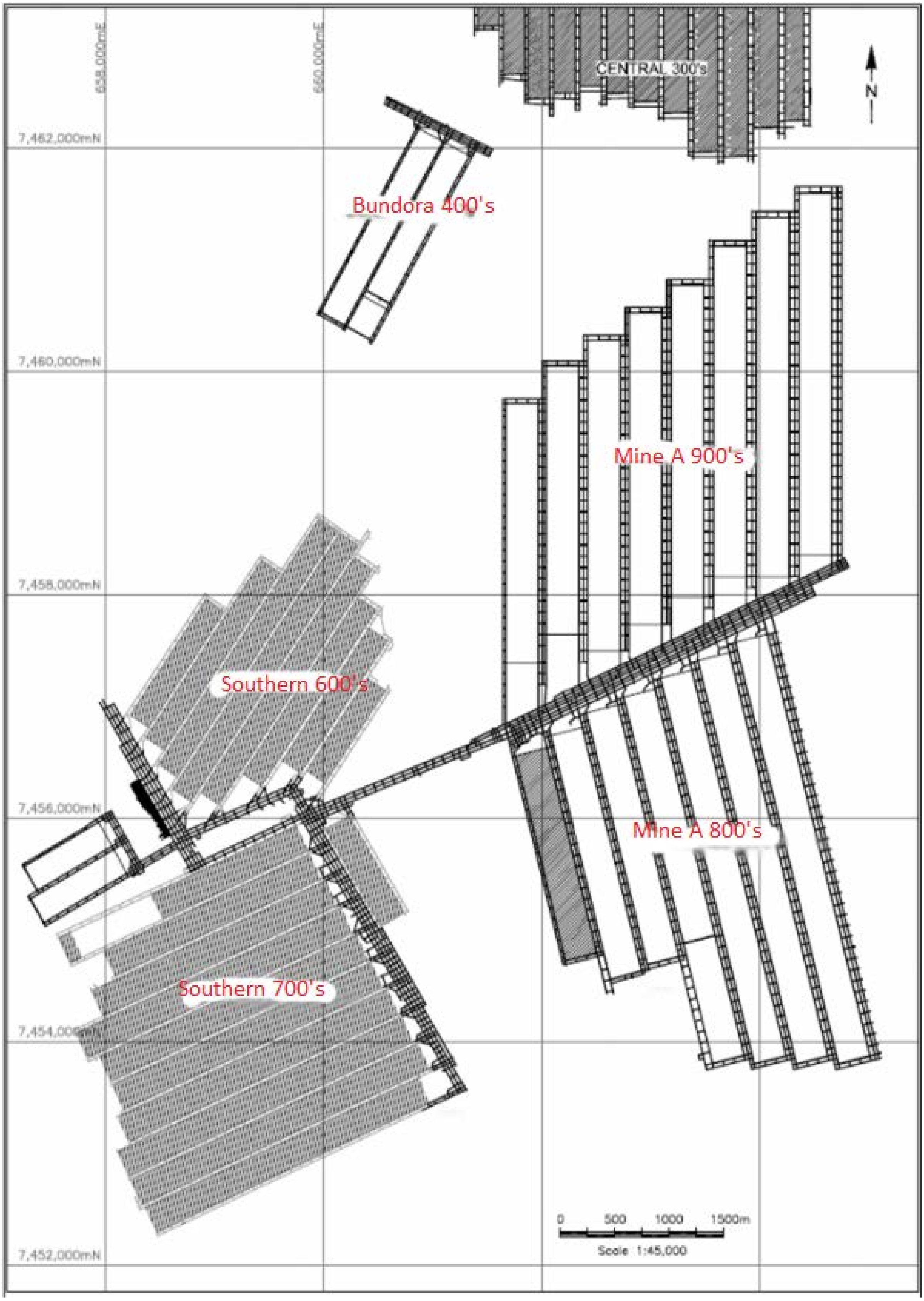

Figure 18. Mine A underground longwall mine layout (Colwell *et al*, 2008)

7.4 DATA COLLECTION

The data used for the analysis of this research study was carried out externally by the site supervisor. It was readily available and contains sets of TC, EC and OC for three different years - 2014, 2015 and 2016. As such it was assumed that the data was sampled using the right procedure, ensuring minimal errors. Additionally, a thorough check was conducted to ensure the data was correct before it was used in the analysis section of this study.

The sampling method used to collect the data is commonly called the personal exposure monitoring. Basically, the selected underground workers carried a sampling instrument with them during their shifts, recording the quantity of DPM in terms of EC, OC and TC. These were recorded in mg/m^3. It is understood that sampling should have been taken from all workers who are exposed to DPM, as supposed to a fraction. However, this is time consuming and too expensive. Hence, a more flexible strategy was implemented, where sampling was done particularly on workers who are at a higher risk of exposure to DPM. This includes personnel operating diesel equipment, mechanics and others who routinely work around diesel vehicles.

Hence, the provided sets of data were analysed through the use of excel software. In each year, the compliance level of the data was investigated along with the relationship between TC and EC.

7.5 RESULTS AND DISCUSSION

This section will present the results obtained from analysing the TC and EC data collected from Mine A underground coal mine. Based on the findings of this case study, it will assist in drawing conclusion regarding the aim of the study.

Since the TC and EC data were collected in three different years, results will be presented according to each year.

A total of 91 samples were collected and given the current TC/EC ratio of 2 as the standard exposure limit, a summary of the compliance of the collected data is presented in Table 6. Most of the data are within the ratio range of 1.5-2.

Table 6.
TC/EC ratio ranges

TC/EC Ratio	2014	2015	2016
1-1.5	13	10	2
1.5-2	18	13	12
3 and above	5	14	5

7.5.1 2014 Results

7.5.1.1 TC/EC Ratio Analysis

There are 35 data sets collected in year 2014 where a TC/EC ratio analysis was conducted to investigate their level of compliance with the current limit. The TC/EC analysis found that five of the samples were not in compliance with the current standard. Contained in Table 7 are the respective samples that were out of compliance, however, sample A127073 and A127072 have TC/EC ratio that is similar to the current standard.

Table 7.
2014 reported EC and TC data

Sample ID	Type	location	Reported DPM Conc (mg/m^3) Elemental Carbon	Reported DPM Conc (mg/m^3) Total Carbon	TC/EC Ratio
A125170	Personal	Surface & UG	0.0.195	0.0487	2.50
A125174	Personal	CT-Headings	0.0209	0.0464	2.22
A125209	Personal	Muster area, Pit bottom & main heading	0.0199	0.042	2.11
A125212	Personal	Pit bottom, GWT	0.0171	0.0375	2.19
A127015	Personal	Not stated	0.0182	0.05	2.75
A127072	Personal	Not stated	0.02	0.04	2.00
A127073	Personal	Not stated	0.0229	0.0458	2.00

To better visualise the TC/EC analysis, Figure 19 shows in graphical form, where five of the non-compliant data sets is shown in red and the current limit in green line.

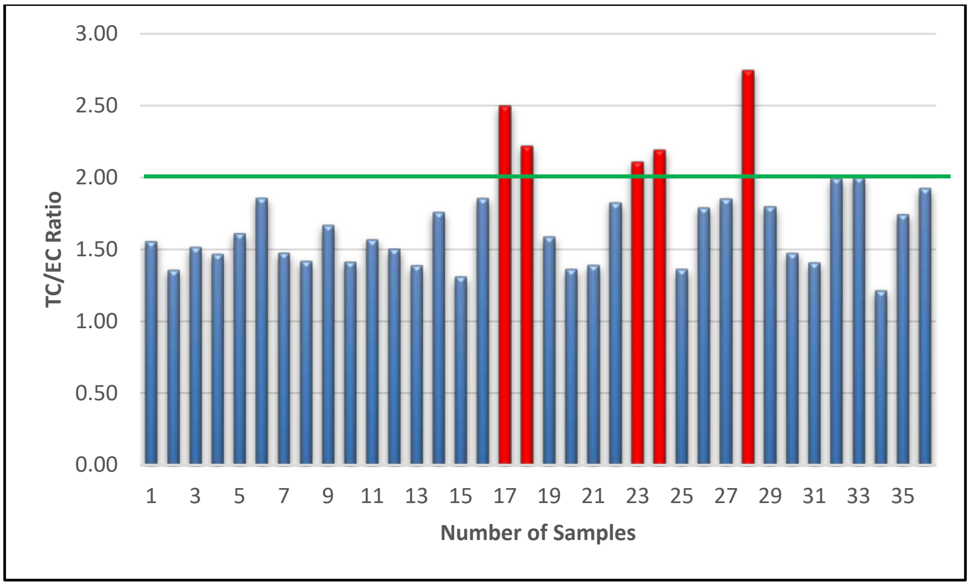

Figure 19. TC/EC analysis (2014)

7.5.1.2 TC and EC Relationship

The 35 data sets of TC and EC were analysed to investigate any correlation and conclusion on the use of EC as a surrogate. As such, a linear graph was produced and a very strong linear relationship between TC and EC was observed as can be seen in Figure 20. The linear relationship between TC and EC has a regression of 0.97, which is very strong and therefore suggests the importance of considering TC in the DPM analysis.

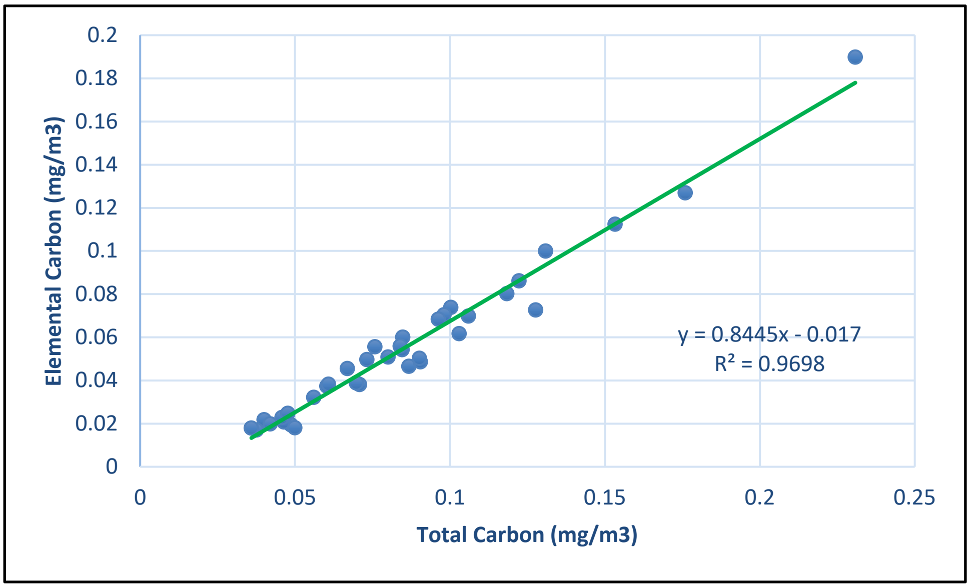

Figure 20. Total Carbon Vs Elemental Carbon (2014)

7.5.2 2015 Results

7.5.2.1 TC/EC Ratio Analysis

In 2015, 37 data sets in total were collected and similarly, a TC/EC ratio analysis was used to investigate their compliance. Out of the 37 data sets analysed, 14 were found to be greater than the current limit of TC/EC 2. These 14 sets of data were tabulated in table 8 below.

Table 8.
2015 reported EC and TC data

Sample ID	Type	Location	Reported DPM Conc (mg/m^3) Elemental Carbon	Reported DPM Conc (mg/m^3) Total Carbon	TC/EC Ratio
A128313	Personal	Assisting Fitter	0.0262	0.0582	2.22
A128361	Personal	903 tailgate	0.0233	0.0505	2.17
A128605	Personal	903 travel route	0.025	0.0621	2.48
A128581	Personal	903 longwall	0.0402	0.0811	2.02
A128302	Personal	903 longwall	0.0466	0.099	2.12
A128636	Personal	Pit bottom	0.0163	0.0455	2.79
A139046	Personal	CT-903	0.025	0.0698	2.79
A139133	Personal	005 Belt	0.0237	0.0514	2.17
A139149	Personal	CT-904	0.0193	0.0498	2.58
A139102	Personal	CT-Mains	0.0116	0.0494	4.26
A129072	Personal	906 Main gate	0.02	0.0636	3.18
A140917	Personal	904 main gate	0.0159	0.042	2.64
A140958	Personal	Bulk head	0.0201	0.0409	2.03
A140972	Personal	Longwall tailgate	0.0225	0.0481	2.14

Figure 21 better illustrate the results for the compliance of the data. 14 of the non-compliant data were shown in red with respect to the current standard (green line). The amount of non-compliant data in this year was greater than in the previous year. It can also be observed from Figure 21 that some data were out of compliance are found within the range of TC/EC ratio of 2.5 and 5. Such results imply the urgent need of reviewing the current limit imposed in Australian mines.

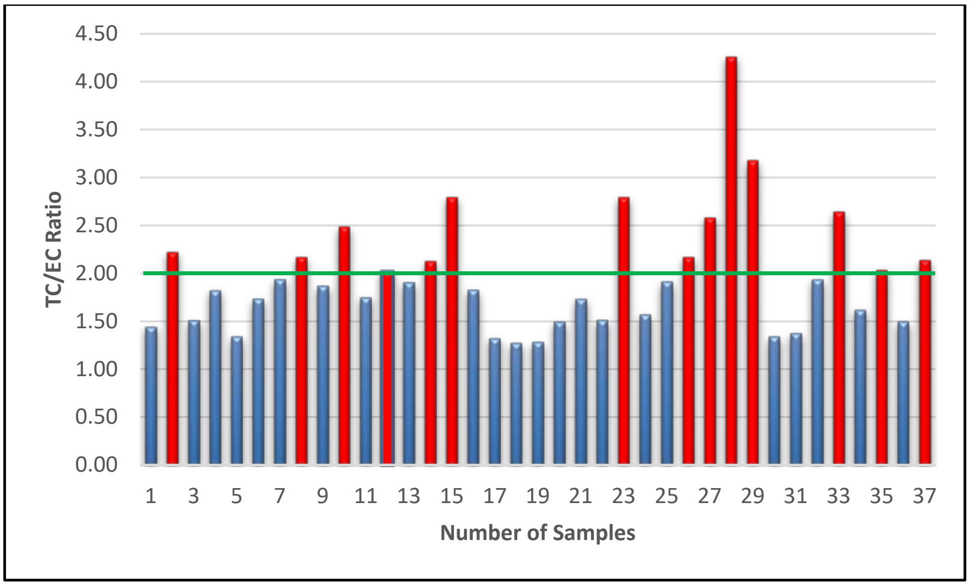

Figure 21. TC/EC analysis (2015)

7.5.2.2 TC and EC Relationship

A similar TC and EC linear analysis was carried out for the data collected in 2015. Again, a linear graph was produced and as expected, a strong linear relationship between TC and EC was achieved with a regression of 0.97. The outcome of the analysis was shown below in Figure 22. Essentially, this result supports the fact that using EC, as surrogate for DPM is insufficient and warrant the investigation of using TC along with EC to form the standards.

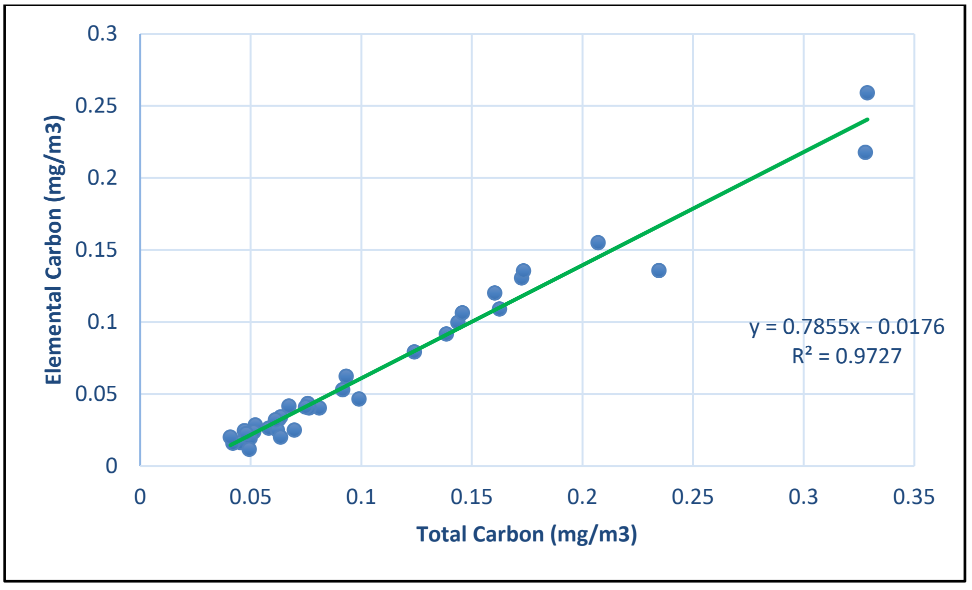

Figure 22. Total Carbon Vs Elemental Carbon (2015)

7.5.3 2016 Results

7.5.3.1 TC/EC Ratio Analysis

In 2016, only 19 data were collected in this particular underground longwall coal mine. Analyses indicated that five samples were out of compliance. Four of the non-compliant data sets were found to be in the range TC/EC of 2.50 and 3. Table 9 contains those 5 non-compliant data found in year 2016.

Table 9.
2016 reported EC and TC data

Sample ID	Type	Location	Reported DPM Conc (mg/m^3) Elemental Carbon	Reported DPM Conc (mg/m^3) Total Carbon	TC/EC Ratio
A141770	Personal	Heading	0.0241	0.0646	2.68
A141811	Personal	CT	0.0239	0.0681	2.85
A141825	Personal	CT	0.0226	0.049	2.17
A141834	Personal	Heading	0.0279	0.0724	2.59
A149153	Personal	907 MG and East mains	0.0269	0.0667	2.48

Similarly, Figure 23 assists in showing the results in graphical form, where coloured in red is the non-compliant data that has TC/EC ratio greater than TC/EC ratio of 2 (green line).

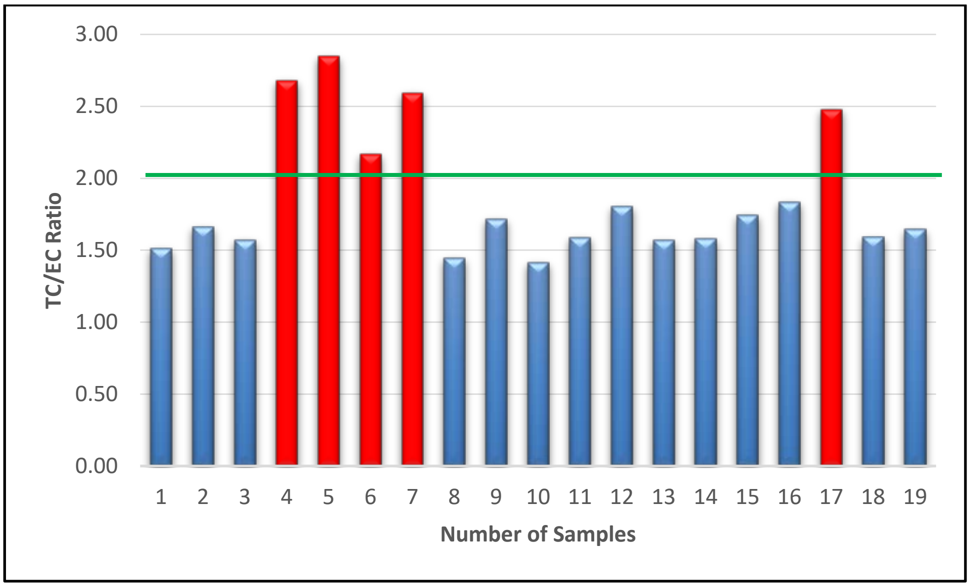

Figure 23. TC/EC analysis (2016)

7.5.3.2 TC and EC Relationship

A linear relationship was also utilised for the 19 data sets collected in year 2016 to investigate correlation between TC and EC. Essentially, the same result observed for the two previous years was also achieved. As can be seen in Figure 24, a strong linear relationship with a regression of 0.90 has been achieved. This result was expected and further supports the aim of considering TC in DPM analysis, as it helps form the condition of a mine.

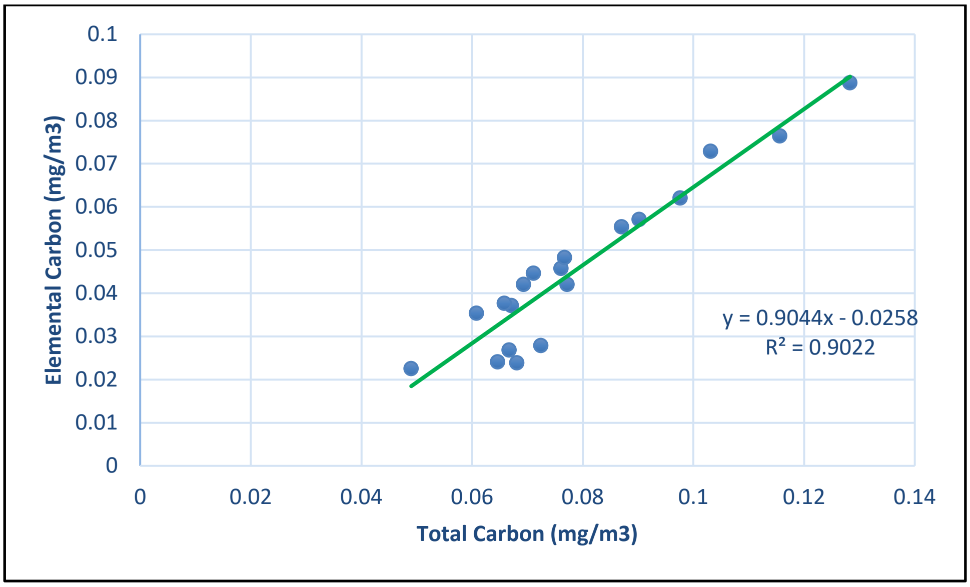

Figure 24. Total Carbon Vs Elemental Carbon (2016)

8 PROJECT MANAGEMENT

8.1 RISK MANAGEMENT

Risk management is a way of identifying the potential hazards that have the potential to cause unplanned consequences involved in the project. Since the site supervisor collected the data externally, the risk assessments regarding the mine site was not included in this risk assessment. However, the risk involved in the completion of the progress report was assessed. Tables 10 and 11 was utilised to assess the risk.

Table 10.
Risk consequence and likelihood classification (Kaplan and Garrick, 1981)

		Likelihood Ranking				
		Common or Frequent Occurrence	Has Happened or is likely to happen on this project	Could Occur or Happened Elsewhere	Not Likely to Occur	Practically Impossible
		A	B	C	D	E
Consequence Ranking	1	1	2	4	7	11
	2	3	5	8	12	16
	3	6	9	13	17	20
	4	10	14	18	21	23
	5	15	19	22	24	25

Table 11.
Risk level classification

Colour	Risk
Red	Extreme (1-6)
yellow	High (7-16)
Blue	Moderate (15-22)
Green	Low (23-25)

Table 12 below contains the hazards and the appropriate measure to control the risks.

Table 12.
Risks evaluation regarding completion of thesis

Potential Hazard	Risks	Risk Factor	Risk Control	Revised Risk Factor
Data Analysis	Physical strain due to in correct working position	18	Ensure seat in appropriate working position	22
	Eye strain due to focussing on screen for a long period	18	Take regular break intervals	21
Information and Research Collection	Excessive information cause headache	16	Take regular break intervals	21
	Texts borrowed from library cause back strains	13	If text is too heavy, request on line version	21
Data Reporting and storage	Written reports and data storage becomes corrupt or lost	9	Saved reports and data in multiple storage device	17
Thesis Completion	High level of stress cause unstable health	14	Proper time management and adhere to schedule task and allocate time to relax	25

8.2 PROJECT TASK AND SCHEDULE

Provided in Table 13 are the proposed schedule for the project, which include the tasks, resource required (assigned in numbers, refer to Table 14), description of task and their expected completion dates.

Table 13.
Outline tasks and completion date

Task	Number Assigned	Description	Completion Date
Research Project Proposal	1,3,4,5,6,8,9,10	Outline the project aims, objectives, scope, problem definition and industrial significance of the research topic	23 Mar 17
Annotated Bibliography	1,3,4,5,8,10	Completion of 10 annotated bibliography as required, to assist in providing basis for literature review	13 Apr 17
Literature Review	1, 3,4,5,8	Review of relevant literature associated with DPM in underground coal mine industry.	9 May 17

Project Progress Report	1,2,3,4,5,6,8,9,	Completion of progress report that contains detail literature review and preliminary data	28 May 17
Project Plan Agreement	8,9	Signing agreement for completion of the project with UQ supervisor	1 Jun 17
Data Collection	2,3,9,10	Acquire all necessary data from external supervisor	Collected
Analysis of Data	2,3,4,9,10	Analysing data to draw conclusion and provide future recommendations	28 Jun 17
Project Presentation	2,3,4,8,9	Presenting the findings base on the research topic	22 Sep 17
Compiling of Report	1,2,3,4,5,6,9	Compiling all literature review, findings, conclusion and recommendation into one final thesis report	8 Oct 17
Final Thesis Report	1, 2,3,4,6,9,10	Completion of the whole thesis project, printed and submitted for marking	9 Oct 17
AusIMM Proceeding	1,2,3,4,9	Completion of conference paper on research topic for reviewing in accordance with AusIMM guide	27 Oct 17

Table 14.
Required resources

Number Assigned	**Resource**
1	Word Document
2	Excel and statistics Software
3	Computer/Laptop
4	Internet Access
5	Library (UQ)
6	Referencing Software
7	Gantt Chart Software
8	PowerPoint Presentation Software
9	UQ Supervisor
10	External supervisor

Provided below in Figure 25 is the proposed Gantt chart showing the major tasks involved in the project with their completion dates.

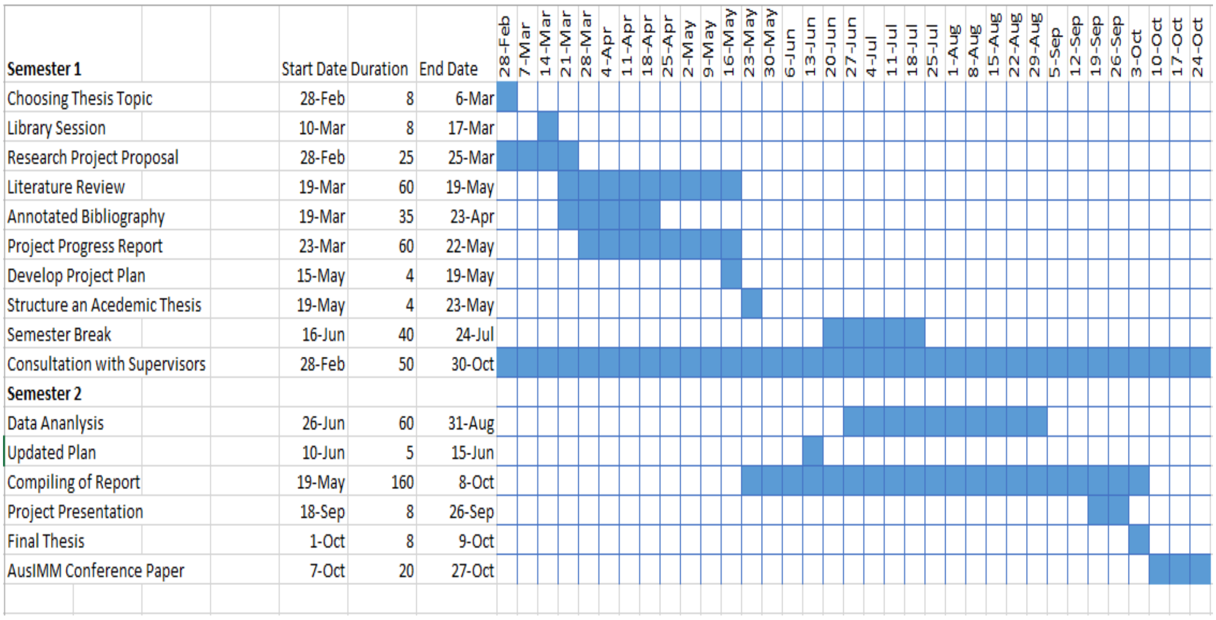

Figure 25. Proposed schedule of tasks shown in Gantt chart

8.3 PROJECT BUDGET

Table 15 contains the estimated cost required to complete this project. The total estimated cost is $27,500 and it is crucial that the project does not exceed the total cost.

Table 15.
Project Budget Estimation

Task	Time (hr)	Salary ($/hr)	Total ($)
Research	120	50	6000
Data collection and analysis	200	50	10000
Thesis Compilation	250	40	10000
Supervisor Consultation	10	150	1500
Total	**580**	**290**	**27,500**

9 CONCLUSION AND RECOMMENDATION

The continually increasing amount of diesel equipment used in most Australian underground mines has shifted the attention of the Australian mining industry to focus on risk assessment and safety. NIOSH and other world health organisations have classified diesel particulate matter from diesel exhaust system as an occupational carcinogen. To ensure a safer and healthier environment for underground mine workers, the reduction of workers' exposure to diesel particulate is essential.

Data collected from Mine A underground coal mine in Central Queensland has been utilised to support the need to reassess the current DPM standard practiced in Australia. This is to provide a safer working environment.

The analysis of TC/EC regarding compliance of data to the current standard has emphasized the DPM issue and the limitation of the current compliance limit practiced in the Australian mining industry. The currently accepted Australian DPM limit was based on the belief that the current standard is balanced by minimising effects of irritation and the potential risk of lung cancer, and the standard limit is achievable as a best practice. However, it lacks definitive supporting data.

Reviewing the current exposure limit is crucial, as the health effects relating to DPM exposure are profound in underground coal miners due to the close proximity of workers to diesel engines. Health issues including acute effects, chronic non-cancer respiratory effects and chronic Carcinogenic have suggested that continual reviewing of the exposure limits is very important. This is because there is real-time measuring equipment available in the market that are capable of measuring real-time TC and EC. Three of such equipment are SKC impactor, D-PDM and Flir Airtec.

Most mining industries have embarked on utilising control technologies to assist in reducing the level of diesel particulate matter. This is to ensure the working environment for underground miners is safer and healthier, which increases the productivity of miners. Significant research was based on fuel quality, ventilation, exhaust treatment devices, engine design and maintenance.

It is believed that the TC/EC ratio is influenced by various factors including interference of coal dust, vapour phase of OC absorbing on filter, size and concentration of dust in the underground coal mine industry. It must be noted and accepted that the TC/EC ratio is expected to vary from mine to mine.

With advances in control technologies and real-time measuring equipment, the use of EC as surrogate for DPM has to be reconsidered. This is because the influence of the TC/EC ratio is significant in establishing an appropriate standard.

Out of the 91 samples collected, 24 samples were out of compliance with the current Australian standard of TC/EC ratio of 2. Five of the non-compliant samples were from 2014 where a total of 35 samples were collected in that year. In 2015, 14 of 37 samples were greater than TC/EC ratio of 2. The other 5 non-compliant samples were found in 2016, where a total of 19 samples were collected. Majority of the samples that are out of compliance are associated with mine workers who are operating, and in close contact with diesel engines. Moreover, a close examination of the sample location indicated that the workers involved in the development heading are of greater risks. This is because of the increased number of diesel powered engines operating within that particular area.

Further analysis on the relationship between TC and EC over the three consecutive years has shown a very strong relationship. This analysis was purposely to investigate the use of EC as surrogate for DPM.

The results of the compliance of data from Mine A coal mine is sound backing to suggest that the current Australian DPM standard for underground coal mines should be reviewed. Failure to do so will result in an out-of-date standard, which will consequently have serious health effects for underground mine workers. Moreover, the strong linear relationship between TC and EC concludes that using EC for DPM analysis to establish DPM standard is insufficient. However, it is more appropriate to consider both the TC and EC.

All in all, it is essential that all Australian underground coal mines to implement strategy to reduce diesel particulate emission. This is because the use of diesel machinery in the mining industry will continue to increase and as such the need of implementing control measures will increase simultaneously.

Therefore, it is very important that future work be conducted in minimising the emission of diesel exhaust as well as investigating different underground coal mines in Australia to establish a more effective DPM standard. This will ensure a safer and healthier working environment for underground mine workers. Furthermore, other areas that further studies can be conducted includes:

- Investigating the relationship between air quantity and DPM; and
- Investigating and comparing the diesel exhaust contain from diesel fuel and biodiesel fuel.

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APPENDIX 1-TC AND EC DATA

APPENDIX 1.1 – TC AND EC DATA (2014)

Table 16.
TC and EC data collected in 2014

Sample ID	Reported DPM Conc (mg/m3) Elemental Carbon	Reported DPM Conc (mg/m3) Total Carbon	TC/EC Ratio
A118129	0.0544	0.0846	1.56
A118045	0.0739	0.1003	1.36
A118153	0.07	0.106	1.51
A118155	0.0456	0.0669	1.47
A118166	0.0375	0.0603	1.61
A118177	0.0467	0.0867	1.86
A118185	0.0803	0.1184	1.47
A118225	0.0863	0.1223	1.42
A118226	0.0618	0.103	1.67
A118258	0.0601	0.0848	1.41
A118280	0.051	0.08	1.57
A118283	0.056	0.084	1.50
A118449	0.127	0.176	1.39
A125135	0.0727	0.1277	1.76
A125141	0.1	0.1309	1.31
A125152	0.0488	0.0905	1.85
A125170	0.0195	0.0487	2.50
A125174	0.0209	0.0464	2.22
A125181	0.0383	0.0608	1.59
A125193	0.1125	0.1533	1.36
A125200	0.0706	0.0981	1.39
A125203	0.0219	0.04	1.83
A125209	0.0199	0.042	2.11
A125212	0.0171	0.0375	2.19
A125189	0.0557	0.0758	1.36
A126817	0.0504	0.0902	1.79
A126824	0.0382	0.0708	1.85

A127015	0.0182	0.05	2.75
A127036	0.0389	0.0698	1.79
A128522	0.0497	0.0732	1.47
A128536	0.0685	0.0963	1.41
A127072	0.018	0.0359	1.99
A127073	0.0229	0.0458	2.00
A127076	0.19	0.2308	1.21
A127084	0.0322	0.0561	1.74
A128514	0.0248	0.0477	1.92

APPENDIX 1.2 – TC AND EC DATA (2015)

Table 17.
TC and EC data collected in 2015

Sample ID	Reported DPM Conc (mg/m3) Elemental Carbon	Reported DPM Conc (mg/m3) Total Carbon	TC/EC Ratio
A128275	0.0997	0.1437	1.44
A128313	0.0262	0.0582	2.22
A128580	0.2179	0.3279	1.50
A128604	0.0286	0.0521	1.82
A128341	0.155	0.2071	1.34
A128362	0.053	0.0917	1.73
A128623	0.0326	0.0629	1.93
A128361	0.0233	0.0505	2.17
A128240	0.0341	0.0636	1.87
A128605	0.025	0.0621	2.48
A128227	0.0434	0.0759	1.75
A128581	0.0402	0.0811	2.02
A128606	0.0402	0.0765	1.90
A128302	0.0466	0.099	2.12
A128636	0.0163	0.0455	2.79
A128314	0.041	0.0748	1.82
A128637	0.1306	0.1726	1.32

A128625	0.2591	0.3288	1.27
A139056	0.1355	0.1734	1.28
A139083	0.109	0.1626	1.49
A139014	0.1358	0.2346	1.73
A139018	0.0917	0.1385	1.51
A139046	0.025	0.0698	2.79
A139019	0.0792	0.124	1.57
A139129	0.0321	0.0613	1.91
A139133	0.0237	0.0514	2.17
A139149	0.0193	0.0498	2.58
A139102	0.0116	0.0494	4.26
A129072	0.02	0.0636	3.18
A139082	0.1201	0.1604	1.34
A139099	0.1063	0.1458	1.37
A140937	0.0244	0.0472	1.93
A140917	0.0159	0.042	2.64
A141037	0.0416	0.0673	1.62
A140958	0.0201	0.0409	2.03
A140963	0.0624	0.0932	1.49
A140972	0.0225	0.0481	2.14

APPENDIX 1.3 – TC AND EC DATA (2016)

Table 18.
TC and EC data collected in 2016

Sample ID	Reported DPM Conc (mg/m3) Elemental Carbon	Reported DPM Conc (mg/m3) Total Carbon	TC/EC Ratio
A141767	0.0765	0.1156	1.51
A141768	0.0458	0.0761	1.66
A141769	0.0621	0.0976	1.57
A141770	0.0241	0.0646	2.68
A141811	0.0239	0.0681	2.85
A141825	0.0226	0.049	2.17

A141834	0.0279	0.0724	2.59
A141785	0.0888	0.1283	1.44
A149098	0.0354	0.0608	1.72
A146965	0.0729	0.1031	1.41
A146975	0.0483	0.0767	1.59
A149105	0.0372	0.0671	1.80
A149123	0.0554	0.087	1.57
A149126	0.0571	0.0902	1.58
A149136	0.0377	0.0658	1.75
A149145	0.0421	0.0772	1.83
A149153	0.0269	0.0667	2.48
A149132	0.0447	0.0711	1.59
A149134	0.0421	0.0693	1.65